



Grant agreement no. 776479

COACCH

CO-designing the Assessment of Climate Change costs

H2020-SC5-2016-2017/H2020-SC5-2017-OneStageB

D1.2 Knowledge synthesis and gap analysis on climate impact analysis, economic costs and scenarios

Work Package:	1
Due date of deliverable:	M 5 (APR/2018)
Actual submission date:	23/07/2018
Start date of project:	Duration: 42 months 01/DEC/2017
Lead beneficiary for this deliverable:	Ecologic Institute
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Summary

This report is a stock-take of the knowledge on the economic costs of climate impacts and policy challenges in Europe. It describes the status quo and gaps in the existing knowledge on impact analysis, economic costs and climate and socio-economic scenarios. The report focuses on the European level but also includes global and national information. It covers models, economic cost estimates and policy challenges for 13 sectors: agriculture, forestry & fisheries, tourism, health, inland flooding & water management, coastal flooding, energy, transport, biodiversity, businesses & insurance.

The most comprehensive coverage on economic assessments of climate costs are found for coastal zones and inland river flooding where comprehensive modeling approaches are already available. For agriculture, energy, forestry, fisheries, transport and tourism, there is some good coverage of cost estimates, but there are still some important gaps that need to be addressed. The coverage of climate cost assessments for business, industry, trade and insurances is limited and biodiversity and ecosystems are areas with a very low coverage on economic assessment of climate change.

The findings of this report will feed into the co-design and development of research questions for the COACCH project.

Disclaimer

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Suggested citation:

Tröltzsch, J., McGlade, K., Voss, P., Tarpey, J., Abhold, K., Watkiss, P., Hunt, A., Cimato, F., Watkiss, M., Jeuken, A., van Ginkel, K., Bouwer, L., Haasnoot, M., Hof, A., van Vuuren, D., Lincke, D., Hinkel, J., Bosello, F., De Cian, E., Scoccimaro, E., Boere, E., Havlik, P., Mechler, R., Batka, M., Schepaschenko, D., Shvidenko, A., Franklin, O., Knittel, N., Bednar-Friedl, B., Borsky, S., Steininger, K., Bachner, G., Bodirsky, B. L., Kuik, O., Ignjacevic, P., Tesselaar, M., Granadillos, J. R., Šcasný, M., Máca, V. (2018). D1.2 Knowledge synthesis and gap analysis on climate impact analysis, economic costs and scenarios. Deliverable of the H2020 COACCH project.

Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	
CI	Classified, as referred to in Commission Decision 2001/844/EC	

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Version log

Version	Date	Released by	Nature of Change
1.0	13/06/2018	ECOLOGIC	First draft version
1.1	08/07/2018	ECOLOGIC	Second draft version
1.2	23/07/2018	ECOLOGIC	Final version

List of Abbreviations

AR: Assessment Report
CAP: Common Agricultural Policy
CGE: Computable General Equilibrium model
CMIP – Coupled Model Intercomparison Projects
CORDEX: Coordinated Regional Climate Downscaling Experiment
DGVM: Dynamic Global Vegetation Models
EAD: Expected annual damage
EAFRD: European Agricultural Fund for Rural Development
EEA: European Environment Agency
EFISCEN: European Forest Information Scenario model
GCM: General Circulation Model
GDP: Gross Domestic Product
GGCM: Global Gridded Crop Models
GHG: Greenhouse Gases
IAM: Integrated Assessment Model
IPCC: Intergovernmental Panel on Climate Change
ISIMIP: Inter-Sectoral Impact Model Intercomparison Project
JRC: Joint Research Centre
PE: Partial Equilibrium model
RCP: Representative Concentration Pathway
SLR: Sea-level rise
SPA: Shared climate Policy Assumptions
SRES: Special Report on Emissions Scenarios
SSP: Shared Socio-economic Pathways
TCI: Tourism Climate Index
TEN-T: Trans-European Transport Network
THC: Thermohaline circulation
WFD: water Framework Directive
WTP: Willingness to pay
VSL: Value of a Statistical Life
WGCM: Working Group on Coupled Modeling

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1. Introduction and Methodology

In the coming years and decades, Europe will experience a range of climate change impacts. These include gradual changes - such as increasing mean temperature and changing precipitation patterns – as well as extreme events - such as flooding, storm surges, flash floods, heatwaves or droughts. Furthermore, there may be important tipping points triggered by climate and socio-economic changes, which are irreversible. All of these effects have the potential to produce increased economic costs which are a key input for policy decision processes.

The objective of the COACCH project (CO-designing the Assessment of Climate CHange costs) is to produce an improved downscaled assessment of the risks and costs of climate change in Europe. The project is proactively involving stakeholders in co-design, co-production and co-dissemination, to produce research that is of direct use to end users from the research, business, investment and policy making communities.

This report is a stock-take of the knowledge on the economic costs of climate impacts and policy challenges in Europe. It describes the status quo and gaps in the existing knowledge on impact analysis, economic costs and climate and socio-economic scenarios. The report focuses on the European level but also includes global and national information. It covers models, economic cost estimates and policy challenges for 13 sectors: agriculture, forestry & fisheries, tourism, health, inland flooding & water management, coastal flooding, energy, transport, biodiversity, businesses & insurance. It takes into account knowledge from past and ongoing EU projects such as ADVANCE, BASE, CARISMA, CO21RIPPLES, INNOPATHS, CD-LINKS, CIRCLE, ClimateCost, DEEDS, ECONADAPT, ENHANCE, EU-Calc, EUROCORDEX, GREEN-WIN, HELIX, IMPACT2C, IMPRESSION, PESETA I,II,III, POCACITO, ToPDAd, TRANSrisk, REINVENT, ROADAPT, WATCH, and others as well as scientific articles. It includes a review on the state of the art of climate change, competitiveness and growth. Furthermore, it provides an overview of existing knowledge on climate and socio-economic tipping points.

The report provides an early framing of possible research topics for the COACCH project. The knowledge and gaps identified by this report also feed directly into the co-design process, where research questions are jointly defined with stakeholders from business, investment, research, non-governmental and policy making communities.

For each sector, studies from EU and national level have been screened to gather information on impacts (slow onset and extremes), including where these are important but have less coverage, climate costs reported, key gaps for cost assessments in this sector, research recommendations and existing policy challenges.

In Chapter 2 of the report, climate projections for Europe are described; in Chapter 3 climate scenarios are summarized. Chapter 4 contains the status quo and gap analysis on climate impacts and policy challenges for 13 sectors. In the final chapter key results are summarized.

The key findings of this gap analysis are summarized in a synthesis document: [The Economic Cost of Climate Change in Europe](#) (COACCH, 2018). As described, the gap analysis provided the basis for a discussion with stakeholders on research questions for the COACCH project. The first COACCH stakeholder workshop was held in May 2018. The discussions are summarized in the COACCH report [D1.3 Workshop results](#).

2. Climate change projections

2.1 State of the art

In the past, a number of scientific initiatives and projects have been undertaken to assess the possible changes that future anthropogenic global warming might induce in the climate of the Earth and also specific experiments have been focused on the European continent. Specifically, climate scenario simulations aimed at quantifying the possible future climate change at the global scale have been conducted through a series of Coupled Model Intercomparison Projects (CMIP). CMIP began in 1995 under the Working Group on Coupled Modeling (WGCM), which is in turn under auspices of CLIVAR and the Joint Scientific Committee for the World Climate Research Program. Such projects supported the development of the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (ARs) on climate and the last CMIP, the CMIP5, paved the way for the 5th Assessment Report (AR5) of the IPCC. The climate community is now performing the last generation Coupled Model Intercomparison Project - CMIP6. The CMIP effort aims to quantify the climate change signal at the global and regional scales, based on General Circulation Models (GCMs) and has been also complemented by additional modelling efforts at the EU scale.

Different EU projects worked and are working at the further development of the climate projections such as the Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (PRUDENCE; Christensen et al., 2007), the Ensemble-Based Predictions of Climate Changes and Their Impacts (ENSEMBLES; Christensen et al., 2009), the Climate change and Impact Research – the mediterranean Environment (CIRCE; Gualdi et al., 2012) and the IMPACT2C project (Jacob et al., 2016).

However, the models operate at a high aggregation level. To address this, studies use downscaling, which is a method that derives local- to regional-scale (10 km to 100 km) information. The Coordinated Regional Climate Downscaling Experiment (CORDEX; Giorgi et al., 2009) vision is to advance and coordinate the science and application of regional climate downscaling through global partnerships and is driven by the World Climate Research Project. CORDEX includes 14 regional domains, where regional downscaling through Regional Climate Models (RCMs) is performed at different resolution, with the most recent projections for Europe assessed under the EURO-CORDEX regional downscaling simulations (EURO-CORDEX; Jacob et al., 2014).

The EURO-CORDEX project uses a multi-model and multi-scenario dataset covering the European domain, at different spatial resolution, from about 50 km (the EUR-44 experiments) up to about 12km (the EUR-11 experiments) until the end of the current century. Such a horizontal resolution, gives the possibility to characterize also changes in extreme weather and climate conditions at the local scale (Scoccimarro et al., 2017; Prein et al., 2016; Jacob et al., 2014).

The basis for climate projections are defined climate scenarios including different potential future Representative Concentration Pathways (RCPs) depending on different potential greenhouse gases (GHGs), Ozone and Aerosol concentration changes in the atmosphere (for more information see chapter 3 of this report on scenarios).

2.2 Climate projections for Europe

The most recent downscale climate projections for Europe are available from EURO-CORDEX. These reconfirm that Europe will warm more than the global average, i.e. Europe will experience more than 2°C of warming (relative to preindustrial levels) even if the Paris goal is achieved in terms of emissions. However, the patterns differ across Europe.

At 2°C of global mean warming, the Iberian Peninsula and other parts of the Mediterranean could experience 3°C of warming in summer, and Scandinavia and the Baltic 4°C of warming in winter. These areas will also reach 2°C of local warming much earlier in time, i.e. in the next couple of decades. These trends are exacerbated under higher warming scenarios. There are also projected increases in extreme events in Europe even for 2°C of global change, which will cause more frequent and severe impacts. This includes increases in daily maximum temperature, extremely hot days and heatwaves over much of Southern and South-Eastern Europe, although relative to current temperatures, there will also be large increases in heat extremes in North-East Europe.

Furthermore, in terms of **heat** stress, the EURO-CORDEX results project an increase of the intensity of extreme events of perceived temperature, taking into account that relative humidity contributes to human discomfort and potential health impacts (Scoccimarro et al., 2017). The analysis also finds these projected increases are robust, even at 2°C warming. (Russo et al., 2015; Sobolowski et al., 2014).

Projected results for the end of the century show an average tendency to more heavy and extreme **precipitation** events across most of Europe throughout the whole year. The model simulations find increases across much of Europe in both summer and winter, with (ensemble mean) intensity increasing by 5% to 15% (and in some areas, even more) under the 2°C scenario. All considered models agree on a distinct intensification of precipitation extremes by often more than 20% in winter and autumn for central and northern Europe. In the Mediterranean area, a large majority of models simulate a reduction of rainy days and mean precipitation in summer (between 10% to 20%), but intermodel spread between the simulations is large. In central Europe and France during summer, models project decreases in average precipitation but more intense heavy and extreme rainfall (Rajczak & Schär, 2017; Scoccimarro et al., 2013; 2016). The projected changes of the European hydrological cycle may have substantial impact on environmental and anthropogenic systems. In particular, the simulations indicate a rising probability of summertime drought in southern Europe and more frequent and intense heavy rainfall across all of Europe. The increases in mean temperature and of extreme events drive the potential increases in flood risk, particularly marked over Eastern Europe and Scandinavia in summer and over Southern Europe in winter (Sobolowski et al., 2014).

While there is a general trend of modest increases of **extreme winds**, the changes are less robust. Nonetheless, there are indications of an increase over some areas of Northern and Central Europe.

2.3 Summary

The natural inter-annual variability of weather/climate, which is simulated by these models, requires the consideration of long time periods, to improve the signal-to-noise ratio. Results are thus typically presented for a period of 30 years. Furthermore, it is easier to identify and

estimate the larger climate change signals arising from large forcings in the period after 2050, than it is to look at short-term climate change. To consider model uncertainty, an ensemble of model runs is usually run.

In general, climate studies hinge on the climate model adequately representing extreme-event statistics: models need to estimate the unforced internal variability of extremes correctly as well as the spatiotemporal pattern of the forced response. This is very challenging for local precipitation extremes, which tend to be underestimated by models.

In the COACCH project, a protocol ([D1.6 Protocol for impact assessment studies](#)) is being developed to sample Regional Climate Models. An example of four possible models is presented in Table 1 below, which include warmer and cooler, and wetter and drier models. The resulting ensemble average, both in terms of averages and extremes can be considered and the associated uncertainty evaluated quantifying the projected spread between models at different future dates. This will consider the use the highest resolution model simulation available for the future period, covering the whole European domain.

Additional studies investigating climate projections of averages and extremes over Europe are necessary, in particular for the definition of potential paths leading to **tipping points**.

The in COACCH used models and scenarios are further discussed in COACCH report [D1.5 Impact and policy scenarios co-designed with stakeholders](#).

Table 1: Regional Climate Models providing atmospheric climate data used by COACCH

Model name	Driving GCM	Institute
SMHI-RCA4	CNRM-CM5	Swedish Meteorological and Hydrological Institute, Rossby Centre
KNMI-RACMO22E	ICHEC-EC-EARTH	Royal Netherlands Meteorological Institute
INERIS-WRF331F	IPSL-CM5A-MR	IPSL (Institut Pierre Simon Laplace) and INERIS (Institut National de l'Environnement industriel et des RISques)
CNRM-ALADIN53	CNRM-CM5	Centre National de Recherches Meteorologiques

3. Socio-economic scenarios

3.1 State of the art

Scenarios play an important role in climate research and assessment, as they provide a consistent qualitative and quantitative description of how key socio-economic parameters may evolve in the future. Scenarios connect different disciplines involved in climate research, in particular integrated assessment, climate modeling, and climate impact research. Using the same scenarios among different disciplines ensures consistency. For example detailed comparable climate data is available for climate impact research, as the climate modeling community has analyzed the same set of scenarios.

Earlier studies (as summarized in the IPCC 4th Assessment Report) used self-consistent and harmonised scenarios (the SRES scenarios), in which future socioeconomic pathways and associated GHG emissions were first assessed, then fed into global and European climate models. These scenarios include a baseline scenario with no mitigation (A1B) and medium to high emissions and a mitigation scenario (E1) in which emissions are strongly reduced.

For the IPCC 5th AR, a new family of climate scenarios was defined, the Representative Concentration Pathways (RCPs). However, these are not aligned to specific socioeconomic scenarios (as in the SRES). Instead the RCPs can be combined with a set of Shared Socio-economic Pathways (SSPs). This provides the flexibility to combine alternative combinations of climate and socio-economic futures.

The four RCPs span a range of future emission trajectories over the next century, with each corresponding to a level of total radiative forcing (W/m^2) in the year 2100 (Table 2). The first RCP is a deep mitigation scenario that leads to a very low forcing level of $2.6 W/m^2$ (RCP2.6), only marginally higher compared to today ($2.29 W/m^2$, IPCC, 2013). It is a “peak-and-decline” scenario and is representative of scenarios that lead to very low greenhouse gas concentration levels. This scenario has a likely (more than 66%) chance of achieving the $2^\circ C$ goal. There are also two stabilization scenarios (RCP4.5 and RCP6). RCP4.5 is a medium-low emission scenario in which forcing is stabilised by 2100. Even in this scenario, annual CO_2 emissions will need to sharply reduce in the second half of the century, which will require significant climate policy (mitigation). Finally, there is one rising (non-stabilisation) scenario (RCP8.5), representative of a non-climate policy scenario, in which GHGs carry on increasing over the century leading to very high concentrations by 2100.

Table 2: Description of RCPs

RCP	Represented pathway	Characteristics
RCP8.5	4.5°C pathway	Rising (non-stabilisation) scenario
RCP6.0	More than 3°C pathway	Stabilisation scenario
RCP4.5	2.5°C pathway	Stabilisation scenario, medium-low emission scenario, mitigation activities are necessary in second half of century
RCP2.6	Well below 2°C pathway	Mitigation scenario, “peak and decline” scenario

The SSPs are the successor of the SRES scenarios published in the year 2000, on which most of the older global and European impact studies are based (e.g. ClimateCost). There are five SSPs, each of which differ with regard to the challenges for adaptation and mitigation (Table 3).

Table 3: Starting points of SSPs. Based on O’Neill et al. (2014) and Riahi et al. (2017).

SSP	Challenges	Key elements
SSP1	Adaptation: low Mitigation: low	<u>Sustainability</u> : Sustainable development, low inequalities, rapid technological change directed toward environmentally friendly processes, high productivity of land
SSP2	Adaptation: moderate Mitigation: moderate	<u>Middle of the Road</u> : An intermediate case between SSP1 and SSP3
SSP3	Adaptation: high Mitigation: high	<u>Regional Rivalry</u> : Moderate economic growth, rapidly growing population, slow technological change in the energy sector. High inequality, reduced trade flows, unfavorable institutional development, leaving large numbers of people vulnerable to climate change
SSP4	Adaptation: high Mitigation: low	<u>Inequality</u> : A mixed world, with relatively rapid technological development in low carbon energy sources in key emitting regions. In other regions, development proceeds slowly, and therefore inequality remains high
SSP5	Adaptation: low Mitigation: high	<u>Fossil-fuel Development</u> : Rapid economic development and high energy demand, most of which is met with carbon-based fuels. Low investments in alternative energy technologies. More equitable distribution of resources, stronger institutions, and slower population growth

The SSPs can be combined with different RCPs, which consists of emission, concentration and land-use trajectories, with corresponding climate projections. Practically all recent climate impact studies on global and European scale are based on the RCPs and SSPs, among which the European projects BASE, PESETA 3, RISES-AM, IMPACT2C and IMPRESSIONS. The global Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) also base their impact modeling on the SSPs.

This combination of SSPs with RCPs involves sampling from a matrix of the different possible combinations of socio-economic and climate assumptions (Figure 1). Some combinations of SSPs and RCPs are not likely, notably combinations of sustainable socioeconomic assumptions with high radiative forcing and vice versa.

Figure 1: Attainability of alternative forcing agents across the SSPs. Source: Riahi et al. (2017)

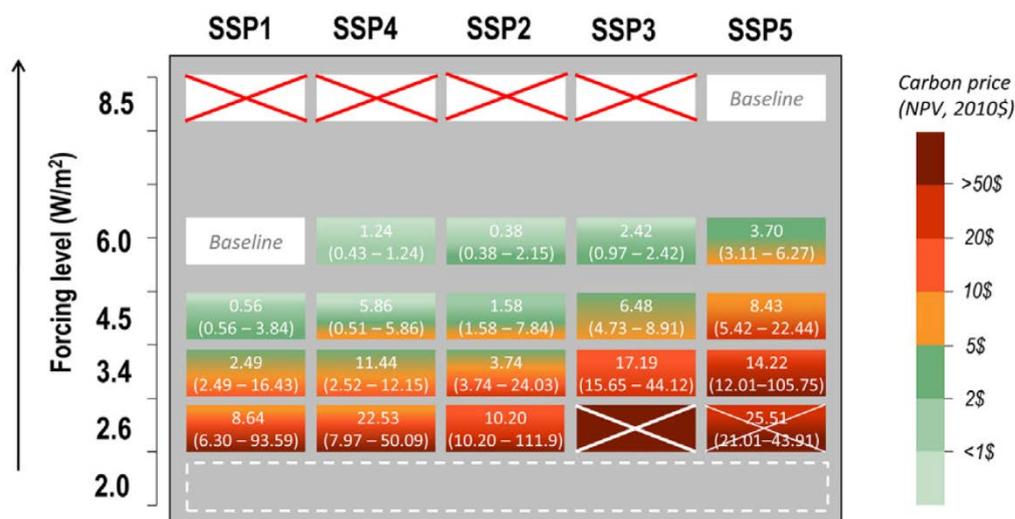


Figure 1 shows that for achieving low radiative forcing levels (4.5 W/m² or below), mitigation efforts are required in all SSPs – with higher efforts required under SSP3 and SSP5. Under the latter two socioeconomic scenarios, a 2.6 W/m² forcing level cannot be attained by the Integrated Assessment Models (IAMs), which integrate climate and socioeconomic modules (see chapter 5). Currently, RCP 2.0 pathways are being constructed to analyze impacts of a 1.5 degree warming.

Finally, to analyze the effect of different mitigation strategies – which are required to meet specified forcing target levels, different Shared climate Policy Assumptions (SPAs) have been identified (Kriegler et al., 2014). All SPAs foresee a period with moderate and regionally fragmented climate action until 2020, but differ in the development of mitigation policies regarding energy (fossil fuels and industry) and land use thereafter (Riahi et al., 2017). Both for energy and land use, three different SPAs are defined. For energy, one SPA has full regional cooperation from 2020 onwards, one assumes a linear convergence to a global carbon tax by 2040, and one assumes a linear convergence to a global carbon tax by 2040 only for rich countries, with developing countries starting and ending convergence 10 years later. For land use, the SPAs differ with respect to pricing of land use emissions: one SPA assumes immediate pricing at the same level as energy GHG emissions, one SPA has limited pricing of land use emissions (0-20% of the price on energy sector emissions), and one SPA depicts an intermediate case between these two extremes.

As of February 2018, SSPs have been used in about 32 studies on water-related impacts, 46 studies on land use, agriculture and/or food, 16 on health impacts, and a further 12 publications about multiple climate change impacts.¹ All of these studies have used at least two different SSPs.

Figure 2 shows the suggested SRES mapping (mentioned above) onto the SSPs and RCPs. The cells in the matrix have entries (black font) where the same SRES scenario approximates a combination of an RCP and an SSP. Here, not only the reference SRES scenarios are mentioned, but also possible positioning of mitigated SRES scenarios. Square brackets

¹ <http://www.cgd.ucar.edu/projects/iconics/publications/#ccimpacts>

indicate mappings that are less robust. The E1 scenario is a mitigation scenario derived from the A1B storyline and leads to a forcing close to RCP2.6.

Figure 2: Scenario matrix architecture showing suggested SRES mappings onto SSPs (in blue) and onto RCPs (red). Source: van Vuuren & Carter (2014).

Challenges to adaptation:		Low		Medium	High	
		SSP1	SSP5	SSP2	SSP3	SSP4
Reference	SRES	B1 / A1T	A1FI	B2	A2	[A2]
8.5 Wm ⁻²	A2 / A1FI		A1FI		A2	[A2]
6.0 Wm ⁻²	B2 / A1B			B2		
4.5 Wm ⁻²	B1	B1	← Mitigated SRES	Mitigated SRES	→	
2.6 Wm ⁻²	[E1]	← Mitigated SRES			→	

Alternative methods

Some impact studies are not based on future socio-economic scenarios, but analyze how future climate could affect the economy as of today (Helix project, PESETA 1 and 2 projects), the so-called comparative static approach.

In the IMPRESSIONS project, for Europe as a whole the SSPs were used, but for individual countries and specific regions (Iberia, Scotland, Hungary, and Central Asia), scenarios were co-designed using stakeholder workshops. The SSPs provided the context to develop these specific scenarios.

Data availability

The SSP scenario drivers consist of population and education (KC & Lutz, 2017), urbanization (Jiang & O’Neill, 2017), and GDP (Dellink et al., 2017; Cuaresma, 2017; Leimbach et al. 2017) projections on a country level. On a more aggregated world regional level, output from IAMs are available on many aspects, such as energy supply and demand (Bauer et al., 2016), land use and land cover change (Popp et al., 2017), greenhouse gas emissions (Riahi et al., 2017), air pollution and aerosol emissions (Rao et al., 2016), and mitigation costs (Riahi et al., 2017). For an overview of the data of SSPs see Riahi et al. (2017) and the [SSP database](https://tntcat.iiasa.ac.at/SspDb/)².

3.2 Sectoral and regional extension of the SSPs

Since the publication of the SSPs, there have been some publications on sectoral and regional extension of the SSPs:

- Several studies provide spatially explicit population and/or GDP projections consistent with SSPs: Jones & O’Neill (2016) for population on a 7.5 arc minute scale, Merkens et al. (2016) for population in coastal zones on a 30 arc second scale, Murukami and Yamagata (under review) for population and GDP on a 30 arc minute

² <https://tntcat.iiasa.ac.at/SspDb/>

scale; Reimann et al. (2018) for population on the Mediterranean coastal zone on a 30 arc second scale;

- Cuaresma & Lutz (2015) have developed projections of Human Development Index based on SSPs which can be used to assess vulnerability to natural disasters;
- There have been some regional extensions of the SSPs to study (sub)national impacts, using among others expert workshops. For Europe, potential interesting articles are Nilsson et al. (2017), who developed site-specific narratives for the Barents region, Haavisto et al. (2016), who developed socioeconomic scenarios for the Eurasian Arctic, Hyytiäinen et al. (2016), who developed storylines of socio-ecological futures in the Baltic Sea region;
- Finally, there are some studies that discuss how specific impact categories relate to the SSPs, notably health (Ebi, 2013), forest management (Kemp-Benedict, 2014), sanitation and wastewater (Van Puijenbroek, 2015), agriculture (Biewald, 2017), and ocean ecosystems and fisheries (Maury et al., 2017).

3.3 Summary

Given that practically all recent impact studies are based on the SSPs, it is proposed to use the SSPs as starting point for the COACCH project to ensure consistency and comparability. However, analyzing the whole SSP-RCP-SPA matrix is too resource-intensive, as this matrix provides more than 100 scenarios (of which 24 baseline scenarios and 81 mitigation scenarios when including different model interpretations of SSPs; see Riahi et al., 2017). To take into account relevant uncertainties without having to analyze a huge number of scenarios, a careful consideration of combination of SSPs, RCPs, and SPAs is needed. COACCH report [D1.6 Protocol for impact assessment studies](#) is preparing an agreed sampling protocol for the RCP-SSPs, taking on board the input from stakeholders on this choice from the co-design workshop (COACCH [D1.5 Impact and policy scenarios co-designed with stakeholders](#)).

It can be argued that for analyzing impacts, SPAs are less relevant, as these mainly affect mitigation costs. However, there are two ways in which SPAs influence impacts from climate. The first one is directly, as different SPAs have (slightly) different temperature pathways throughout the century. The second is indirectly: the way in which climate change impacts GDP partly depends on the economic structure, which is affected by mitigation. This implies that the same climate change projections can have different GDP impacts under different mitigation assumptions. However, both effects are arguably relatively small compared to the effect of different SSPs and RCPs.

A remaining question is how to deal with adaptation in the scenarios. Ideally, under each of the proposed combinations of SSPs and RCPs, we would define an optimal and sub-optimal adaptation scenario. However, this would lead to a doubling of the scenarios to be considered. Another option could be to analyse different levels of adaptation for a selection of SSPs, providing a good picture of the whole uncertainty range.

4. Economic costs estimates and policy challenges

In this chapter economic costs and policy challenges regarding climate change are reviewed. The research is based on a literature review including EU and national projects and scientific articles. The work covers 13 sectors: agriculture, forestry & fisheries, tourism, health, inland flooding & water management, coastal flooding, energy, transport, biodiversity, and business & insurance. Based on the review, key gaps per sector were synthesized. Based on the key gaps, research questions were developed and discussed during the first COACCH stakeholder workshop (see [D1.3 First working group meeting, bi-lateral meetings, and scenario workshop](#)). The key gaps for each sector are summarized in a table including an estimation of quantity and quality of available information for different impacts.

4.1 Agriculture

Introduction

Climate change has the potential to lead to major effects in the agriculture sector, including changes to production, as well as changes to the risk of extreme events, shifts in the range and prevalence of pests and disease, etc. These could have potentially negative effects, e.g. from lower rainfall or increasing variability, but also potentially positive effects, e.g. regarding CO₂ fertilization, or extended growing seasons from changes in mean weather variables. These will lead, in turn, to effects on aggregate production, supply chains, prices and trade. There are also possible risks to food security and the breakdown of food systems. There is a large body of existing literature focussing on long-term (50-100 years) impacts of average climate change (slow onset) on agricultural production (Chen, McCarl, and Schimmelpfenning, 2004). Research into variance and increased frequency of climate extremes, however, has lagged behind.

Methods for economic assessment

Climate impact studies generally use an impact chain starting from climate models that assess the effect of climatic trends on temperature and precipitation. Subsequently, resulting temperature and precipitation changes on crop yields can be studied either by using biophysical process based crop growth models, and their gridded derivatives sometimes referred to as the Global Gridded Crop Models (GGCMs), or by using statistical models. Examples of statistical models estimating crop yield responses are provided by Sun et al. (2007); Chen, McCarl, and Schimmelpfenning (2004); and Ray et al. (2015). GGCMs aim to model key processes affecting plant growth dynamics, by simulating a wide range of exogenous variables such as weather, plant genotypes, environmental factors and management styles on plant growth. Especially in the last two decades, GGCMs have been tailored more to the inclusion of environment and management indicators, such as temperature, CO₂, and ozone, allowing them to analyse crop and management options under different climate patterns (Hatfield et al., 2011; Pathak & Wassmann, 2009; Rosenzweig et al., 2013). An overview of seven crop models and the way they model (extreme) climate events is provided in Annex 1: Comparison of the main elements of crop models.

Statistical models use reduced-form equations to estimate the effect of historical temperature and precipitation data on yield variability (Mistry, Wing, and De Cian, 2017),

and can disentangle the role of shocks, though they are based on historical data and thereby less suited for considering possible future extreme events. Comparison of the two methods by Lobell & Asseng (2017) concluded that for low levels of warming, there are no systematic differences in impact measured between the two methods. However, for larger warming, systematic differences are observed because process-based crop models typically include CO₂ effects of global warming, whereas statistical models typically do not (Lobell & Asseng, 2017).

To represent the influence of yield changes on agricultural markets, partial and general equilibrium (PE and CGE) models, as well as various econometric approaches or simulation models are often used (Moss et al., 2010; Nelson et al., 2014; van Meijl et al., 2017; Wiebe et al., 2015). With their economy-wide structure, the current Computable General Equilibrium (CGE) models can assess not only the effect on land-based sectors that are primarily affected by climate change but also the other sectors via indirect income and price effects. Partial Equilibrium (PE) models focus on the land-based sectors only, but with more detail and a larger number of endogenous variables. PE and CGE models and a wider array of economic models can also be used to look at adaptation (from farm level adaptation with crop models, through to international trade effects). An overview of ten PE and CGE models in terms of how climate-induced yield changes can react to cropland expansion and crop productivity is provided in Annex 1. Only a few of these models attempted to analyse also the effects of extreme weather events. One of these models is GLOBIOM in which annual weather variability and climatic shocks will result in deviations from expected prices and yields (Boere, Havlik and Gaupp, 2017).

Econometric approaches have also been developed with Ricardian models and time-series or panel-data models. The former exploit the spatial variation in land value and climatic conditions, estimating the long-run relationship between the two, providing an analysis of the direct welfare measures of climate change impacts on farmers, because the dependent variable is typically land value, rent, or farm profit (Mendelsohn & Massetti, 2017). The key advantage of the panel-data approach lies in the possibility to control for any confounding factor that is time-invariant within each unit of observation via “fixed effects”. This is particularly useful in the analysis of agricultural activity as many farm/firm or local characteristics of economic activities that strongly affect production outcomes, such as soil quality and management ability, are simply not observable in the majority of datasets. In addition, fixed-effect accounts for the exogeneity of weather shocks with respect to the choice of farm/firm inputs (Hsiang, 2016; Blanc & Schlenker, 2017). Finally, in principle, panel-data models can potentially consider time fixed effects to the same external shock, such as a variation in the level of prices, the introduction of a government policies or any other macro-economic shock. The major drawback of the Ricardian approach are the omitted variable bias, as well as the distortionary effect of the poor functioning of land markets, which is particularly severe, especially in developing countries.

However, the panel-data approach has limitations, too. Firstly, when the key variable of interest, as in the case of temperature, displays a small within time variation, then the presence of measurement errors in weather data could induce an attenuation effect, biasing the estimated coefficient towards zero. The second big challenge facing panel-data studies is their ability to capture farmers’ adaptation, especially in the long-run.

Climate cost estimates

There have been numerous studies analysing production changes in Europe, though far less on the economic consequences. The results of crop modeling studies tend to show a strong distributional pattern in Europe, with productivity gains in the North and losses in the South.

The PESETA study (Ciscar et al., 2012) used crop model outputs in a CGE model and estimated the climate-induced impacts in agriculture in Europe would reduce GDP by 0.3%, which is mainly caused by a reduction in consumption. The economic impacts are spatially highly disaggregated, with small productivity and economic gains observed in the Northern European regions and larger losses observed in the Central and Southern European regions. The PESETA II study (Ciscar et al., 2014) built upon this work and reported climate-induced losses in total monetary terms. It estimated climate related costs for agriculture of €18 billion/year in Europe by the 2080s for the A1B reference scenario, driven by yield reductions of 20% in Southern Europe. These can be reduced by EUR 2 billion under a +2°C global warming scenario. In the short-term, the study found technical adaptation can improve the yields to a large extent, with a general improvement all over Europe (except for the Iberian Peninsula).

The ECONADAPT project assessed market driven (autonomous) adaptation around demand and supply responses using a global multi-country, multi-sector CGE model (CAGE-GEME3), which included an analysis of the agriculture sector (Ciscar et al., 2016). At the global level, market-based adaptation reduced climate damages by a third for both GDP and welfare losses. It considered three key responses: labour mobility, both across sectors and region; the degree of substitutability between capital and labour in the production function; and the degree of substitutability for trade flows and domestic production. Within the EU, the welfare-enhancement effect of adaptation is smaller at lower latitudes in the agriculture sector. The analysis in Europe found that market driven benefits were greatest in Northern Europe, but smaller in Southern Europe, reflecting the size of impacts and potential for substitution.

Balkovic et al. (2015) estimated the difference in welfare (the sum of producer and consumer surplus) with and without climate-induced yield shocks using the partial-equilibrium model GLOBIOM for a 2°C scenario (mid-century). They found that when adaptation was included, climate change had an overall positive monetary aggregated impact on land-use related sectors in Europe of USD +0.56 billion/year, but found a loss of USD 1.96 to 6.95 billion/year without adaptation. Balkovic et al. (2015) acknowledge the high uncertainty of these estimates, further highlighted by the large differences compared with the PESETA II study. These large uncertainties are partly due to the estimation on yield impacts and the assumptions on the climatic trend. Hence, the damage estimation is directly related to the production losses estimated using crop models, which in turn is directly dependent on assumptions on rainfall and precipitation patterns estimated using climate models.

However, most studies trying to estimate climatic impacts on the agricultural sector are limited in their scope in terms of crops, and focus mostly on the arable sector and differ in terms of scenarios, adaptation options and farm behavior (Iglesias et al., 2012). Impacts of climatic extremes on agricultural losses are currently not considered in the estimation of economic costs, while they can be of paramount importance (Ciscar et al., 2014).

Furthermore, the results of the existing economic studies vary with the climate, crop and economic models used and key assumptions made (CO₂ fertilisation, interplay between sectors) and on international effects (demand, supply and trade). A major inter-comparison initiative (the Agricultural Model Inter-comparison and Improvement Project, AGMIP) investigated these issues. This found that climate change could lead to a 20% (mean) food price rise in 2050 globally, but with a large range from 0% to 60% (Nelson et al., 2014) across the models. Yield losses and price impacts rise more sharply in later years under higher warming scenarios. These results only cover a limited number of crops and impacts, and exclude horticulture, livestock, and impacts on the wider multi-functionality of agriculture.

Policies and challenges

Climate events affect harvests and motivate policy-making, both in the form of disaster-relief and in the form of design and adoption of policy instruments to initiate adaptation activities. The integration of climate events in climate scenarios and climate-induced crop yield impacts in partial and general equilibrium models provides a unique opportunity to estimate climate impact costs and evaluate potential climate adaptation policies, noting both adaptation and mitigation policies affect the extent to which agricultural production and related socio-economic indicators will be impacted by climate events.

Iglesias et al. (2012) listed adaptation measures according to the main climate-related risk that they would tackle and the potential costs and benefits that the measure would involve. For example, they categorize the introduction of pesticide application and improving nitrogen fertilization as low cost-low benefit option. In line with Lobell & Burke (2008), Iglesias et al. (2012) categorize changes to crops and cropping patterns, cultivation practices and the introduction of drought-resistant crops would involve low to medium costs and benefits. Arguably, the adoption of different varieties or management practices could reduce climate sensitivity without a shift in the spatial allocation of production. However, in practice, this adoption mechanism has not really taken into effect (Lobell & Tebaldi, 2014). Adaptation costs are higher for more structural measures such as the introduction of new irrigation areas.

Pathak & Wassmann (2009) found that only high-intensity irrigation provided a viable adaptation mechanism against wheat yield drops in drought-prone years. Storage is another potential adaptation mechanism, as analyzed by, amongst others, Ermolieva et al. (2016), Femenia (2015), and Burrell & Nii-naate (2013). The suitability of adaptation measures is also highly dependent on the crop and region studied. Lobell & Burke (2008) found that South Asia and Southern Africa will be especially negatively impacted due to climate change without proper adaptation measures.

The most well-known framework for agriculture-related climate adaptation policies are related to the EU's Common Agricultural Policy (CAP). The current CAP is organized in two pillars: Pillar I which mainly involves direct payments and Pillar II comprised of the European Agricultural Fund for Rural Development (EAFRD). The total amount of CAP funding over the period 2014-2020 amounts EUR 362,787 billion, of which EUR 277,851 billion (76.5%) are allocated to Pillar I and EUR 84,936 billion (23.4%) to Pillar II.

As part of Pillar I, producers can be compensated for providing public goods in the form of environmentally-friendly farming practices – a so-called greening component that is added to the basic payment if farmers are in compliance (European Commission, 2014). Pillar I measures could potentially enhance market stabilization and food and nutrition security

under climate change by (1) providing a lower-bound to farmers' revenues through direct payments and thereby safeguarding farmer's existence and food production; (2) securing environmental safety through the basic practices to qualify for green payment. Under the second pillar, one can think of policies aimed at innovation and knowledge exchange, enhancing competitiveness, promoting food chain organisation and risk management, restoring, preserving and enhancing ecosystem services, resource efficiency and low carbon and climate resilient agriculture, and poverty reduction. Measures to enhance market stabilization and food and nutrition security under climate change may include physical investments such as irrigation infrastructures that may lead farmers to cope better with dry spells, and may allow production in areas where rain-fed cultivation is not possible; restoring agricultural production. Preservation of farming practices which have a beneficial effect on the environment and climate and foster the changes needed is another measure within Pillar II of the CAP, as well as risk-reducing strategies such as insurance for crops, livestock and plants, mutual funds for adverse climate events, animal and plant diseases, pest infestations and environmental incidents that may lead farmers to cope better with production shocks.

On 1 June 2018 the European Commission published the legislative proposal for the future CAP for the period 2021-2027. It includes a proposal for CAP strategic plans which would be prepared by each of the member states and would be based on specific national needs to reach the EU's CAP objectives (European Commission, 2018).

Key gaps

The main focus to date has been on medium to long-term productivity changes and studies have not analysed inter-annual price fluctuations, e.g. from extreme weather events. There has also been less coverage of what happens when yields and prices diverge away from market equilibria. Most studies tend to focus on the optimisation of welfare or profit along a single pathway for a single scenario and further work is needed on uncertainty (multiple futures and costs) and on capturing and designing robust adaptation responses especially in the long term. For mitigation policy, a key consideration is the interaction between agriculture, forestry and bio-energy. Finally, further research on unexpected shocks in agricultural supply and markets, as well as longterm tipping points, are also a priority.

Table 4: Summary of key gaps: Agriculture

Summary: Agriculture		
Impact / topic	Quantity and quality of information	Key Gaps
Impacts		
<i>Robustness of assessment (variety of climate scenarios)</i>	<i>Moderate</i>	<i>Analysis of different climate scenarios on the agricultural sector to provide robust climate cost estimates</i>
<i>Crop impacts</i>	<i>Poor to good depending on the model</i>	<i>Adapt crop models and statistical approaches towards the assessment of the impact of climate events on yields</i>
<i>Climate impacts on food system and market distortions</i>	<i>Poor to good depending on the model</i>	<i>Climate impacts on food system and market distortions</i>
<i>Tipping points</i>	<i>Poor</i>	<i>Climate impacts on food systems and market distortions that are so severe that markets and food systems cannot recover.</i>
<i>Interactions between agriculture and forestry</i>	<i>Poor to moderate</i>	<i>Climate-induced interactions between the forestry, agriculture and bio-energy sector (e.g. through land-competition and deforestation)</i>

	<i>depending on the model</i>	<i>for land expansion), quantification of indirect climate impact costs</i>
<i>Interactions between agriculture and fishery</i>	<i>Poor</i>	<i>Climate-induced interactions between agriculture and fisheries(e.g. through competition for aquaculture feed and via substitution of food items)</i>
<i>Comprehensive estimate of climate impact costs with and without adaptation under different climate policies</i>	<i>Poor</i>	<i>Framework for consistent assessment of mean climate change and extreme event and expectation formation</i>
Policy challenges		
<i>Policy effectiveness for different spatial scales</i>	<i>Poor to moderate depending on model</i>	<i>Suitability of policies to a geographical scale (assess direct and indirect impacts for different geographical levels)</i>
<i>Policy effectiveness short-term vs. long-term activities</i>	<i>Poor to moderate depending on model</i>	<i>Suitability of policies for short-term disaster relief versus and long-term climate adaptation</i>
<i>Analysis of NDCs or ambitious climate mitigation activities</i>	<i>Poor to moderate</i>	<i>Assessment of reduced climate impact costs of Nationally Determined Contributions (NDCs) or more ambitious climate targets</i>
<i>Costs and benefits of adaptation and mitigation policies</i>	<i>Poor to moderate</i>	<i>Assessment of adaptation and mitigation policies in respect to various socio-economic goals (e.g. reduction of price volatility and market-related distortions).</i>

4.2 Forestry and Fisheries

Introduction

Projections of the net effects of climate change on **forestry** are complex. Tree growth may be enhanced by some processes (including CO₂ fertilisation, warmer winter weather and longer growing seasons), but might be negatively affected by others (such as from reduced rainfall). Climate change contributes to the rate, frequency, intensity and timing of disturbances and its impact on forest ecosystems is expected to increase. Changes in temperature and the availability of water affect the health and productivity of different species. Increased periods of droughts and warmer winters are expected to further weaken forests against invasive species and incidence of pests. Damage to forests will also occur due to extreme weather events; extreme events such as storms can damage or destroy trees and stands, whilst droughts can make forests more vulnerable to secondary impacts (e.g. increased risk of fire and vulnerability to biotic damage). There are also additional risks from forest fires, affecting both managed and natural forests.

Regarding **fisheries**, the future impacts of climate change are expected to result in a number of changes in the abiotic (i.e. sea level, sea temperature, oxygen levels, salinity) and biotic (i.e. primary production, food webs) conditions of the sea, affecting the reproductive success, growth and size, disease resistance but also the distributional patterns of fisheries (OECD, 2016). Expected effects are due to e.g. change of evaporation and precipitation, water runoff, higher incidence of storms and extreme weather events, and changing sea ice conditions (Cheung et al., 2011). Fishing is a "harvesting" activity and human activities dominate the abundance and distribution of many European marine organisms: climate change is an additional pressure on fish stocks whose resilience is already low. The

significant risks do not only impact marine ecosystems, but freshwater fisheries and aquaculture as well (Ficke et al., 2007, Cochrane et al., 2009). The impacts of climate change are already being observed in European Seas, leading to changing composition of local and regional marine ecosystems, and thus fisheries.

Methods for economic assessment

There are existing European (and global) models that are used to assess the potential effects of climate change on **forest**, notably Dynamic Global Vegetation Models (DGVMs). However, European forests are very diverse in their response to climate change and vulnerability of forests is dependent on geographical location, landscape and tree species, which makes analysis challenging (especially capturing local effects). There are also forest management models, which are traditionally based on historical productivity and site conditions, and are used to optimise the commercial management of forests. The results of these models can be fed into partial equilibrium or general equilibrium models. The European Forest Information Scenario model (EFISCEN) is widely used for different EU policy assessments (Schelhaas et al., 2006; 2016), often together with IASA's Global Forest Model – G4M (Kindermann et al., 2013).

The main approach used for **fisheries** is physical modelling using ecological trophic modeling (Tam et al., 2008); statistical analysis (Gephart et al., 2017); statistical forecasting (Klyashtorin, 2001); time-series analysis (Britten et al., 2015); GIS based analysis (Handisyde et al., 2006) and a number of coupled modeling approaches: hydrodynamic and ecosystem coupled modeling (Merino et al., 2012); and coupled physical–biogeochemical modeling (Blanchard et al., 2012).

Climate cost estimates

There is relatively little economic analysis of the impacts of climate change on forestry and fisheries.

Studies show that optimal altitude for **forest species** is changing on average about 30 m (with the range of -170 to +240 m for different species) per decade in France and Spain (Bastrup-Birk et al., 2016). This will have economic consequences. Economics of forests under climate change is considered in some recent publications (e.g. Lintunen & Uusivuori, 2016), but not really included in the models. An exception is provided by Hanewinkel et al. (2009) who estimated the costs of having to shift from Norway spruce (*Picea abies* (Karst) to European beech (*Fagus sylvatica* (L) for a forest area of 1.3 million ha in southwest Germany to be in the range of EUR 690 million to 3.1 billion.

Hanewinkel et al. (2013) estimated the impact from future temperature increases in Europe by 2100, analysing 32 tree species. The analysis projected the expected value of European forest land will reduce due to a decline in economically valuable species. Depending on the discount rate and scenario (used SRES A1B, B2 and A1F1), this indicated a 28% reduction (with a range of 14% and 50%) in the present value of forest land in Europe, with a cost of several hundred billion Euros.

Increased periods of droughts and warmer winters are expected to further weaken forests against invasive species. The Outlook for the Development of European Forest Resources (Schelhaas et al., 2006) provides the methodologies, data, scenarios, and results of the outlook on the European forest resources from 2000 to 2040. The document considers

geographic Europe and found that the demand for wood will be higher (2-11%) than European wood harvests in all scenarios.

In Europe alone, fires impact more than half a million hectares of forest annually with overwhelmingly negative consequences: fires devastate the carbon storage of forests and can lead to large economic damages (approximately EUR 1.5 billion/year) and loss of life (San-Miguel-Ayanz & Camia, 2010). According to the IPCC (2014) fire frequency and wildfire extent will increase in Southern Europe (Lozano et al., 2017). Current 100-yr wildfire events will occur every 5-50 years (Forzieri et al., 2016). Khabarov et al. (2016) mention an increase of burned areas in Europe of 200% by 2090 (compared to 2000-2008). In the PESETA II project (Ciscar et al., 2014) it was estimated that burned area due to forest fires could more than double in the Southern European region in the reference simulation, reaching almost 800,000 ha. Lee et al. (2015) describe wildland fires in the US in a reference scenario and a scenario with GHG mitigation policies. For the reference scenario, 7,800 moderate and severe fires are projected for the US; 1,650 more compared to the mitigation policy scenario. The economic impacts in the reference scenario are USD 3.5 billion higher than in the mitigation policy scenario. The economic evaluation is based on avoided cost of offsetting actions on conservation lands due to the wildland fire.

Logan et al. (2003) summarize that forest insects and pathogens in North American forests are the most pervasive and important agents of disturbance, affecting an area almost 50 times larger than fire and with an economic impact nearly five times as great. Climate change will interact with forest disturbances, such as pathogens, insects and fire, to impact growth and species variety of the world's forest tree species. Outbreaks of forest diseases due to native and invasive forest pathogens are predicted to become more frequent and intense as drought and other abiotic factors are amplified under climate change. (Sturrock et al., 2011).

Regarding **fisheries** there are several global and regional studies on changes in annual catch and the redistribution of stocks or catch potential (Cheung et al., 2009; Cheung et al., 2010; Cheung et al., 2013; Blanchard et al., 2012; Merino et al., 2012; and Barange et al., 2014). Generally, it is expected that productivity will increase in high latitudes and decrease in mid-to low latitudes (IPCC, 2014). Cheung et al. (2010) project changes in global catch potential from 2005 to 2055 under climate change scenarios. They show that climate change may lead to large-scale redistribution of global catch potential, with an average of 30–70% increase in high-latitude regions and a drop of up to 40% in the tropics by mid-century. Sumaila & Cheung (2010) estimate reduction of current gross revenues by up to USD 40 billion/year for global fisheries due to severe climate change and continued overfishing. Some studies suggest changes may already be happening in important European fisheries (Perry et al., 2005; Rijnsdorp et al., 2009). A study by Link & Tol (2009) analysed economic impacts on Barents Sea fisheries, especially cod and capelin fisheries, due to climate change and changes in Atlantic thermohaline circulation (THC). Changes in hydrographic conditions have an impact on recruitment success and survival rates. The economic development of the fisheries is determined for the 21st century, considering a purely stock size based and a coupled stock size-hydrography based harvesting strategy. A substantial weakening of the THC leads to changes in cod stock development resulting in unprofitability of linked fishery in the long run.

Policies and challenges

The **EU Forest Strategy** from 2013 emphasised the effects of climate change on forests as one priority area. The new strategy was developed to provide a framework to better tackle the new challenges facing forests and the forest sector, including the growing demands on and threats to forests. For 2018, a review of the EU Forestry Strategy is planned. First evaluations of the forestry measures are already published, e.g. EEIG Alliance Environnement (2017). Policy challenges are discussed in the EU Forest Strategy as well as in other official EU documents on climate change (e.g. EU, 2006; European Commission, 2007); many topical questions and recommendations are considered in publications (e.g. Urwin & Jordan, 2008; Lindner et al., 2010; Spathelf et al., 2014; amongst others).

Three main policy questions are discussed in the literature. First, the costs of inaction, as well as the costs of climate impacts with and without adaptation under different climate policies and different climate and socio-economic trajectories. This is targeting the question of which type of policies are able to mitigate climate-induced changes that affect forest growth as well as afforestation, deforestation and forest management decisions. Second, selection and development of European/national (state) policies with respect to forms of forest management that would be able to increase resilience of forest cover and reduce impact of disturbances – from close-to-nature forestry and continuous forest-cover forms of sustainable forest management (Hengeveld et al., 2012) through to multifunctional forestry with defined management priorities to short-rotation energy plantation (Kolström et al., 2011). This problem should be considered at a landscape level, taking into consideration forest priorities for all stakeholders. Third, the lack of proper economic valuation of ecosystem services, particularly the trade-off between different services which could be substantially different (e.g. from synergetic to tolerant to competitive to exclusive). The solution to the latter question would define a real price of forests. Currently this problem is considered based on expert opinions of stakeholders (Constanza et al., 2017).

A number of policy and options are available to reduce the fire risk associated with anticipated climate change. In addition to improvements in active response through better fire suppression (Khabarov et al., 2016), there is also a range of preventive strategies such as prescribed burnings (Silva et al., 2010; Khabarov et al., 2016), management options aimed at restricting the potential spread of fire (e.g. utilizing agricultural fields as fire breaks) (Lloret et al., 2002), and long-term options that include increases in rotation length and changes of tree species (Schelhaas et al., 2010). Various combinations of reactive and preventive measures can also be pursued to reduce risk, improve flexibility, and optimize the use of available resources. Development of wildfire risk management concepts based on a socio-ecological approach is important for Europe (Tedim et al., 2016). Restoration of mined peatlands can effectively lower the risk of deep burns and corresponding carbon emissions in Northern Europe (Granath et al., 2016).

The **European common fisheries policy**, updated in 2014, is managing European fishing fleets and conservation of fish stocks. The aims are to ensure that European fisheries and aquaculture are environmentally, economically and socially sustainable. It plays an important role in its commitment to sustainable exploitation of European fisheries (Guillen, 2016). The predicted redistribution of fish stocks and catches as a result of climate change is most directly related to another critical policy issue in fisheries, namely the already high level of overfishing and the mounting pressures on marine resources even in the absence of climate change (Brander, 2008). The state of wild fisheries and the prospects for future

production and the future fish populations are the subject of intense debate. Some authors in recent years have predicted nothing less than a total collapse of all fisheries before 2050 (Worm et al., 2006). That view has since been moderated, and the rebuilding of stocks is considered possible with reform (Worm et al., 2009). Another recent modeling exercise projected a decline of six major wild fish stocks by the year 2048 (Quaas et al., 2015). Other studies and some international institutions are indicating that global catches are on a path to slow recovery and could remain stable or even increase slightly, but only with continued reform and regulation (Costello et al., 2016; World Bank, 2016). In this regard, the new European common fishery policy plays an important role in its commitment to sustainable exploitation of European fisheries (Guillen, 2016).

Aquaculture can play an absolutely critical role in alleviating the pressures on capture fisheries and the future of the seafood markets will largely depend on the ability of aquaculture to deliver (Msangi and Batka, 2015). In the EU, the importance of the aquaculture sector is reflected in the mandatory implementation of national multiannual aquaculture plans in member countries, and the ambitious targets of aquaculture growth contained therein (European Commission, 2016). In this context, the environmental performance of aquaculture and the environmental problems of this sector are all the more important. Farmed fish rely on wild catch for feed, exerting pressure on wild stocks, and sometimes inverting food chains feeding natural prey with natural predators (Naylor et al., 2000). Other areas of concern are fish escapes, genetic contamination, pollution, and threats to biodiversity (Diana, 2009). On the other hand, the aquaculture sector lags other livestock meat producing sectors in its path along the Environmental Kuznets Curve (Asche, 2008).

Key gaps

There is a need for further economic analysis of impacts on production, consumption and markets for forestry products, as well as land-use interactions with the agriculture sector. There are gaps on the economic costs on wildfires, changes in pests and diseases and on wider ecosystem services, as well as large-scale tipping points. There are also many gaps for fisheries, with a need to advance the economic modelling on marine fisheries and aquaculture production, and to better understand key effects such as ocean acidification.

Table 5: Summary of key gaps: Forestry and fisheries

Summary: Forestry and fisheries		
Impact / topic	Quantity and quality of information	Key gaps
Impacts		
<i>Forest productivity and forestry</i>	<i>Poor to moderate</i>	<i>Nutrient limitation and nitrogen budgets are not considered in forest models. Economic models are lacking in many countries. Changes in management decisions due to actual climate impacts and anticipated climate impacts are not considered.</i>
<i>Shifts in forest species composition</i>	<i>Moderate</i>	<i>Lack of methodologies and models considering shift of optimal climate condition for different tree species and ability (natural and due to management) of forest to change</i>
<i>Pests and disease</i>	<i>Poor</i>	<i>Economic estimates are limited</i>
<i>Forest fire</i>	<i>Poor</i>	<i>Methodologies to include disturbances are missing</i>
<i>Interactions between forestry and cropland</i>	<i>Moderate</i>	<i>Interactions between forestry and agricultural sectors often not fully understood, e.g. impacts on food systems and land use</i>
<i>Landscape resilience</i>	<i>Poor to moderate</i>	<i>Lack of considering the structure of forest (agroforest) landscapes and corresponding forest management actions aiming at increasing</i>

		<i>resilience of the landscapes as a whole</i>
<i>Fisheries</i>	<i>Poor to moderate</i>	<i>Climate impacts on aquaculture, capture fisheries productivity needs to be included in economic models. Further integration of ecological and economic models necessary.</i>
Policy challenges		
<i>Climate mitigation policies for forestry sector</i>	<i>Moderate</i>	<i>Estimation of effects for policy scenarios of forest protection and afforestation for climate change mitigation, including NDCs</i>
<i>Climate adaptation activities in the forestry sector</i>	<i>Moderate</i>	<i>Economic estimates of adaptation activities, e.g. effects due to changed management decisions due to actual and anticipated climate impacts</i>
<i>Ecosystem services valuation</i>	<i>Poor</i>	<i>No formal methods/ models for assessing trade-off of ecosystems services for portfolio of policies</i>
<i>Wildfire prevention</i>	<i>Poor</i>	<i>Policy scenarios to reduce risk and severity of wildfire are missing</i>
<i>Performance of aquaculture production</i>	<i>Poor</i>	<i>Environmental performance of aquaculture production, sourcing of fish feed, and sustainability as compared to capture</i>
<i>Impacts of more sustainable fishing quotas on aquaculture and terrestrial food production</i>	<i>Poor</i>	<i>Pathways to achieving sustainable capture fisheries production, and resulting redistribution of capture production, and feed substitution</i>

4.3 Flooding and Water Management Risk

Climate change is projected to alter global and regional water cycles, though these changes will not be uniform, with differences between wet and dry seasons (IPCC, 2013), arising from changes in precipitation, temperature and evapo-transpiration, snow recharge and glacier melt, etc. This is likely to intensify a number of economic risks, including more frequent and/or intense floods, and changes to the water supply-demand balance including potential water deficits and water quality (IPCC, 2014).

4.3.1 Flooding

Introduction

Floods are among the most important weather-related loss events in Europe and have large economic consequences. Indeed, there have been a number of recent severe flooding events, which have led to major losses. Climate modelling suggests that, in the coming decades, climate change will intensify the hydrological cycle, and increase the magnitude and frequency of intense precipitation events in many parts of Europe.

Projections of future climate change (Field et al., 2012; IPCC, 2013) suggest extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century. Where future rainfall intensity increases, or where heavy rainfall events become more frequent, this has the potential to increase flood risks, either related to river floods or surface water floods (flash floods) (Kundzewicz et al., 2014). These lead to a number of potential impacts, which include tangible direct damage or physical damage to buildings, intangible impacts that arise in non-market sectors (such as fatalities, ecosystem damage), indirect damage to the economy (Koks et al., 2013), such as disruption to transport, supply chains or electricity supply, and indirect intangible losses, such as subsequent disease outbreak or mental health impacts. Analysis by Hallegatte & Przulski (2010) shows that

indirect flood impacts are mainly relevant for very large disasters (e.g. New Orleans, Katrina, 2015) where it may contribute up to 50% of the total losses. For smaller events, the contribution of indirect damages is generally smaller.

Methods for economic assessment

There are a large number of studies of the economic costs of future river floods at the European, national and local scale. Most studies use hydrological models that link flood hazard (extreme flood events) and exposure, then use probability-loss (depth) damage functions to capture the impacts of events of different return periods. These are then integrated into a probabilistic expected annual damage (EAD). These models can also capture existing flood protection and consider adaptation protection levels.

Climate cost estimates

There are several pan-European studies estimating the economic costs of future river flooding in Europe using two major high-resolution flood risk models. Roudier et al. (2016) using the LISFLOOD model estimated the EAD from climate change will rise from EUR 4-5 billion/year (currently) to EURO 32 billion/year in the EU by the middle of the century (RCP4.5 at 2°C for mean model results, combined socio-economic and climate).

Earlier LISFLOOD studies (Rojas et al., 2013) found that costs increase significantly for higher emission pathways, especially by the 2080s (with estimates of EUR 98 billion/year by the 2080s for A1B) and also found that uncertainty was large. It is important to note, however, that roughly half of these future costs are due to socio-economic changes (i.e. population and economic growth), with the other portion being linked to climate change. These studies show an important distributional pattern, with high climate-related costs in some EU Member States. As highlighted by Jongman et al. (2014), these results indicate that the EU Solidarity Fund may face a probability of depletion. However, the LISFLOOD modelling found that adaptation increased protection could significantly reduce these damages cost-effectively.

A similar approach was followed by Deltares within the EU-FP7 BASE project. The exposure assessment is based on land cover maps (e.g. CORINE 2006) which are converted to rasters for different damage categories (e.g. residential, commercial, industrial, infrastructure, agriculture). The vulnerability assessment is done using EU-average depth-damage relations for each land use class. The resulting damage is calculated for all return periods, which are then translated to a damage-probability curve to obtain flood risks expressed in terms of expected annual damage (EAD). According to BASE, the EAD of the baseline scenario (1960-1999) was EUR 16 billion, which will grow to 26-27 billion by 2030 (RCP 8.5 and 4.5 resp.) and to EUR 28-33 billion by 2080 (RCP 4.5 and 8.5 respectively), assuming no adaptation (Bouwer et al., 2018).

The advantage of these top-down approaches is that they give EU-wide estimates of the costs of flood events, and give insight in the relative flood damages in different member states. However, these models are not accurate enough to provide in-depth estimates of local flood damages, for which river basin scale models should be used. A growing number of such studies is being undertaken, which are complemented by local catchment and city scale studies. There are also important surface water flood risks, especially for urban areas, that are not captured in the studies above and require local modelling.

On the national/river basin scale, a large variety of approaches exist in analysing flood risks and assessment of flood risk management strategies, using different definitions (e.g. types of flooding), assumptions, metrics (e.g. return periods, analysis methods, GIS, historical data, modelling) which makes it very hard to compare outcomes. The EU Flood Directive offers a mechanism to harmonize the way in which damages are calculated. The BASE project showed that it is currently very difficult to harmonize the results of the EU top-down models with the local models. This still is a large challenge for modellers: how to integrate or harmonize top-down and bottom-up modelling approaches?

With regard to modelling the indirect costs of flood risks, important work has been done by Koks (2016). He integrated direct and indirect cost modelling for the Rotterdam harbour and compared different economic impact models for Italy. More importantly, he developed a multi-regional model to estimate the indirect effects of several flood events in Europe to arrive at similar EAD estimates as used in direct model approaches. He estimated the indirect EAD at EUR 1.9-3 billion/year for Europe (Koks, 2016). Note that infrastructure is only one of the routes by which these indirect damages propagate through different sectors.

A team of researchers at IVM (VU University) recently developed a comprehensive model of flood risk on a local scale (Ward et al., 2017). This framework will be appended by the state-of-the-art dataset on European river protection standards in Europe (Aerts et al., 2016).

Policies and challenges

The EU Floods Directive (2007/60/EC) requires all member states to assess their flood risk in three steps: 1) undertake preliminary flood risk assessment, 2) develop flood hazard and risk maps and 3) develop flood risk management plans for areas under high risk. These steps are reviewed in a 6-year cycle. The results of the 2nd preliminary flood risk assessment, with special attention for climate change, are expected by December 2018, corresponding hazard and risk maps by December 2019. The most recent evaluation report of the first (preliminary) round (Nixon et al., 2015a; 2015b) reports considerable differences between EU member states. For example, the overview of historic floods is not consistent among countries. With regard to expected floods, not every member state includes the same types of flooding, but most include large river (fluvial) floods because this typically concerns a transboundary issue, to be dealt with in the European context. Also, different methods are used to assess flood risks, in terms of: models (hydrologic and hydraulic routing); GIS analysis; return periods (varying from 5-1000 years), representation of retention areas; representation of flood protection infrastructure and inclusion of geomorphological characteristics. Methodological documents describing the underlying methods were often missing, or expert judgment was used rather than models, so that a quantitative comparison is currently not possible (Nixon et al., 2015a; 2015b). However, member states generally agree that economic damage is the most important consequence of floods, followed by human health, environment and cultural heritage. In their analysis, 16 out of 23 participating member states already started accounting for the impacts of climate change on flood occurrence, the number of states accounting for development of settlements, infrastructure and socio-economic development is much smaller (Nixon et al., 2015a; 2015b).

The largest policy challenge might be the development of sound adaptation strategies and the representation of those strategies in EU-scale models. In general, hazard assessments in

models are quite accurate, but the representation of adaptation strategies is very difficult. Some studies have addressed the effects of adaptation measures (Rojas et al., 2013; Ward et al., 2017; Alfieri et al., 2016b). Within the BASE project, Bouwer et al. (2018, under review) introduced the concept of ‘opportunity tipping points’, to underpin improvements in European flood protection levels and adaptation with a cost-benefit analysis.

We observe that there is a lot of ongoing scientific work on (direct and indirect) costs of river flooding (see model section), however that this is rarely included in flood protection policies. On a national scale, the Dutch government (2014) has supported the new risk based flood protection strategy with such a cost-benefit strategy (Kind, 2014), based on a monetary rational optimal flood defence level. The EU Floods directive does not aim at or require a cost-benefit rationality from member states. COACCH could provide input to the discussion whether such an approach could be useful for other member states as well. One could question whether action should be taken when the benefit:cost ratio is >1 (a rational flood defence level), given the large uncertainties that surround the analyses. It seems that in many European countries, budget constraints mean that governments only invest at significantly higher benefit-cost ratios. (cf. Flikweert, 2015). We also observe that many member states focus their investments in flood risk management on improving emergency response, rather than flood prevention.

It is important to note that the economist’s cost-benefit rationality is not always useful for the policy maker. The ‘Expected Annual Damage’ metric smooths out very large events that have the highest indirect costs and it gives little insight into the large uncontrollable extreme events (tipping points) that the policy maker may wish to avoid under any circumstance. Tipping points related to flooding may occur due to the flooding and failure of critical infrastructures, such as data-centres, energy production and transmission, transport infrastructure, etc. Avoidance of these events, i.e. those with disproportionately large socio-economic consequences, is an interesting direction of research to focus on besides the cost-benefit perspective, and it is gaining importance in the discussion on disaster risk management and climate adaptation. Including the failure of such critical infrastructure could also underline the importance of mitigation policies (in reducing the risks of very high impact events).

Key gaps

At the European scale, state-of-the-art estimates of EAD (Expected Annual Damage) for river floods exist at a high resolution. However, work is still needed to reconcile top-down and bottom-up (local) studies and improve model validation. There is also a need to improve the indirect costs and intangible impacts of flooding and to better represent adaptation (including costs and benefits) in the models. It is stressed that the focus on EAD gives little insight into large extreme events which have high policy resonance, thus there is also a need to further consider these events. The relation between direct and indirect costs of flooding need to be analysed further, especially with regard to (critical) infrastructure and built environment. A final priority is to advance surface flooding estimates.

Table 6: Summary of key gaps: Flooding

Summary: Flooding		
Impact / topic	Quantity and quality of information	Key gaps
Impacts		
<i>EU top-down river flood models</i>	<i>Moderate</i>	<i>Mismatch between bottom-up (national/river basin) and top-down (EU scale) models</i>
		<i>Validation of top-down models</i>
		<i>Multi-flood hazards cannot be assessed in current top-down EU model frameworks</i>
<i>Indirect costs of flooding</i>	<i>Poor</i>	<i>Estimating indirect costs of flooding, particularly through failure of critical infrastructures</i>
Policy challenges		
<i>Accounting for different drivers in flood risk policies</i>	<i>Moderate</i>	<i>Accounting for climate change in flood risk estimates</i>
		<i>Impact of socio-economic developments not included in flood risk studies</i>
<i>Costs estimates of adaptation strategies to underpin flood risk policies</i>	<i>Poor</i>	<i>Understanding of strengths and weaknesses of cost-benefit approaches towards flood risk management and potential gaps</i>
		<i>Improved assessment of total flood costs (direct + indirect + intangible) to underpin flood risk policy</i>

4.3.2 Water supply and management risks

Introduction

Water supply and wastewater services are vulnerable to climate change impacts (Loftus et al., 2011). In addition to risks to water resources (and deficits) across multiple sectors, there are also risks to water infrastructure and water quality, as well as specific activities that depend on water (e.g. hydro-power, river transport, power station cooling, irrigation). However, while the contrast in precipitation between wet and dry regions and between wet and dry seasons is projected to increase (IPCC, 2013) there will be regional exceptions and the projections are uncertain, making adaptation challenging. Impacts can be expected from reduced water availability and supply rates, and from inadequate design capacity of stormwater infrastructure in case of (flash) floods. Flooding and sea level rise can also affect other water infrastructure, e.g. pumping stations and treatment plants and pipes. Another aspect is a poorer water quality due to increased temperature or changes in flows (Loftus et al., 2011).

Methods for economic assessment

Economic assessments in the water sector are based on elaborated regional hydrological models, combined to integrated (dynamic) hydrological-economic models. A set of studies has been based on integrated assessment analysis, and use hydrological and water management models at river basin levels to consider cross-sectoral demand as well as supply. Macroeconomic models are used as well, e.g. Bank of Greece (2011) used a cross-sectoral general equilibrium model (GEMINI E3) to evaluate the total environment, economic and social costs of climate change and adaptation in Greece. Partial equilibrium models are used for analysis of the water sector, e.g. Barker, Murray and Salerian (2010) model the urban water sector.

Climate cost estimates

The high site specificity and the need to consider multiple sources of water demand makes analysis at the European scale challenging. There have been European wide assessments of the impacts of climate change on stream-flow drought, soil moisture drought and water scarcity in the IMPACT2C project (IMPACT2C, 2015), but these were not monetised.

However, there are studies assessing the cost of adaptation in the sector, and these are a proxy for damages. Hughes et al. (2010) estimated adaptation costs for all water services (i.e. water resources, treatment and networks; sewage networks and treatment) at USD 110 billion (cumulative) for Western Europe and USD 104 billion (cumulative) for Eastern Europe, in the period 2010–50. The EC (2009) also reports that the cost of desalination and water transport in 2030 could range from EUR 8.5 to 15 billion/year. A further study (Mima et al., 2011) estimated the additional costs of increased electricity demand for water supply and treatment (due to increasing water demand from climate change) at EUR 1.5 billion/year by 2050 and EUR 5 billion/year by 2100 for the A1B scenario, falling significantly under an E1 scenario.

At the country level, the Bank of Greece (2011) calculated the cost of climate change to the water supply sector under different climate change scenarios and time horizons. For the A2 scenario over the 2041-2050 period, the cumulative cost of climate change is projected at 1.32% of GDP, increasing to 1.84% between 2091-2100. Under the A1B and B2 scenarios, the costs are lower; about 0.9% of GDP, and decrease during the later time period (to about 0.5% of GDP in 2091-2100). The Net Present Value of total damage to water reserves are estimated for the A2 scenario with 3.2% of GDP (discount rate 0%) and 1.7% for discount rate of 1%.

On a regional scale, Metroeconomica (2006) estimated the economic losses of foregone water use due to water deficit in regions of the UK under four climate-socioeconomic scenarios. In southeastern England, the total annual economic losses in the region during the 2080s ranged from GBP 41.7 million (Global Sustainability Low Emissions scenario) to GBP 388 million (World Markets High Emission scenario).

In Switzerland, EPFL (2017) note that various cantonal case studies provide mixed results on climate change impacts on the water management sector by 2060. Two different climate scenarios have been used. In the canton of Aargau, an increase in flood events could increase maintenance costs in the water sector by 10 to 50% depending on the climate scenario. An increase in occurrence of dry spells in Aargau potentially will increase the operation costs for drinking water provisioning up to 10% in a strong climate scenario. In contrast, Graubünden expects that changing precipitation patterns could lead to a slight reduction of the risk of drinking water shortage. For the canton Uri, a mountainous region, damages from mudslides to water management infrastructure are estimated to increase by 10% to 30% in 2060 (depending on the climate scenario).

Policies and challenges

The main policy in the water sector is the **EU Water Framework Directive (WFD)** including the implementation via River Basin Management Plans and Programmes of Measures. The WFD has regular review and management cycles. The RBMPs have to be updated every six years, and the third RBMPs need to be prepared for 2021. A fitness check of the WFD and Floods Directive was announced by the European Commission in autumn 2017 and this

should be finalized in third quarter of 2019. The main European financing for water infrastructure is delivered via EU Regional Policy and especially the Cohesion Fund. The Cohesion Fund invests in drinking water supply, treatment of wastewater and solid waste. Guidelines for the mainstreaming of climate change (climate proofing) in the Cohesion Policy have been published together with the EU adaptation strategy (see SWD (2013) 135: European Commission, 2013).

Further challenges arise related to adaptation strategies – particularly related to drought management. This will be especially relevant for countries in the Mediterranean region, which already display different approaches to drought legislation that is integrated into water management to varying degrees (Iglesias et al., 2007). A key factor for effective water and drought management is the definition of institutional roles and responsibilities, and many countries currently observe low levels of cooperation between these institutions at the river basin, regional, and State level. Furthermore, Iglesias et al. (2007) highlight the importance of integrating drought management into long-term water management strategies and the development of specific drought contingency plans. Specific issues are also likely to be seen related to water reuse and desalinization, as well as irrigation. Finally, the suitability of economic instruments with regards to water and drought management (i.e. water markets, tariffs) remains an open question, with experiences demonstrating success in some countries but not others.

The concept of adaptive strategies (approaches designed to modify and change over time through a learning process and in light of new information) is certainly not new in the field of water management. The ability to treat uncertainty, even deep uncertainty, is crucial when incorporating climate change into planning. However, experience has shown that institutions can face challenges when shifting their approaches from more traditional, static planning, to implementing adaptive strategies (Lempert & Groves, 2010).

Key gaps

There is limited knowledge base on climate costs for the water sector on EU level. Cost assessments especially for adaptation activities are provided on regional, river basin or local level, partially including projection of damage costs.

Table 7: Summary of key gaps: Water supply and management risks

Summary: Water supply and management risks		
Impact / risk	Quantity and quality of information	Key gaps
<i>Water supply</i>	<i>Poor</i>	<i>Analysis of cross-sectoral effect of water and potential cascade effects to all sectors, Integrating cumulative pressures in assessment</i>
<i>Water demand</i>	<i>Poor</i>	<i>Cross-sectoral studies (linking e.g. energy, industry, households), Integration in economic models</i>
<i>Water quality</i>	<i>Poor</i>	<i>Biophysical and hydrological models need to be further developed and linked with economic assessments</i>

4.4 Coastal flooding

Introduction

Coastal zones contain high population densities, significant economic activities and ecosystem services. These areas are already subject to coastal flooding and climate change has the potential to pose increasing risks to these coastal zones in the future. There are a number of potential risks from climate change on coastal zones, from a combination of sea level rise (SLR), storm surges and increased wind speeds, risks of flooding, loss of land, coastal erosion, salt water intrusion and impacts on coastal wetlands.

Methods for economic assessment

The economic costs of coastal impacts – and adaptation – are among the most comprehensively covered area of study. Methods for assessing large scale coastal flood risk have developed and been widely applied, at multiple scales, though estimates vary strongly with the sea level rise scenario considered, the digital elevation input data and population sets used, and the consideration of existing protection.

Coastal climate change impact assessments on global and continental scale currently concentrate on coastal flooding. While there are a few studies that assess erosion (Hinkel et al., 2013) or wetland change (Spencer et al., 2016) on global scale, flooding is generally considered as the most severe impact in coastal areas (Wong et al., 2014). Data and methods for assessing large scale coastal flood risk assessments have developed rapidly (Abadie et al., 2016; Diaz, 2016; Hallegatte et al., 2013; Hinkel et al., 2014; Vousdoukas et al., 2016, Vitousek et al., 2017). However, estimates vary strongly with the sea level rise scenario considered, the digital elevation input data and population sets used, the consideration of existing protection and large uncertainties remain leading to wide ranges of results including:

Regional SLR patterns: local SLR impacts can vary between -20% (4,549 km²) and +25% (7,093 km²) for 21st century cumulative loss of land due to enhanced erosion and between -25% (64 million) and +60% (137 million) for the annual number of people affected by coastal flooding at the end of 21st century between regional SLR patterns of individual climate models (numbers here refer to an ensemble mean SLR of 35cm with ensemble mean of 5,665 km² lost land during 21st century and 83 people flooded annually in 2100) and ensemble mean patterns (Brown et al., 2016).

Available elevation and population data: different digital elevation models and population datasets can lead to differences of 150% in area estimates and 160% in population estimates. These differences are most extreme below 1 m elevation. Population counts below 1 m elevation range from 1% to 2.3% of the total global population (Lichter et al., 2011). Such differences can lead to differences up to 50% in flood damages by 2100 (Wolff et al., 2016).

Adaptation strategies and models: without adaptation 0.2–4.6% of global population is expected to be flooded annually in 2100 under 25–123 cm of global mean sea-level rise, with associated expected annual losses of 0.3–9.3% of global GDP (Hinkel et al., 2014). Adaptation through dikes reduces impacts by 2 to 3 orders of magnitude with global annual investment and maintenance costs of USD 12–71 billion in 2100. Other studies have similar findings. Under 21st century SLR of 0.3 to 1.3m and SSP2, adaptation reduces global net

present costs of SLR by a factor of seven as compared to no adaptation, when applying a discount rate of 4% (Diaz, 2016). Recent studies extend this kind of analysis by finding that for 12% of the global coastline, which corresponds to 84% of global floodplain population, it is economically robust to invest in protection, i.e. protection is cheaper than not protecting under 21st century SLR scenarios from 0.3 to 2m, discount rates from 0 to 6% and all SSPs (Lincke & Hinkel, 2018). Regions with high population growth and high exposure to coastal flooding have been identified where protection measures for building resilient coastal communities are essential (Neumann et al., 2015). However, no migration due to SLR has been assumed in this study.

Subnational coastal population dynamics: Neither coast-ward migration nor coastal urbanisation as a driver of migration nor land-ward migration as a response to increased flood risk is taken into account in existing studies. When also accounting for subnational human dynamics, population living in the Low Elevation Coastal Zone could be 85 to 239 million higher compared to only considering national population change (Merkens et al., 2016). The effect of land-ward migration on coastal flooding impacts has not considered yet in studies.

Coastal flooding frequency assumption: this point originates from Buchanan et al. (2017) stating that the majority of research on SLR and coastal flooding (including AR5) use a Gumbel distribution to characterize SLR and flooding frequency curves. This method assumes that the increase in the frequency of flooding is invariant across different levels of flooding, leading to over estimation of hazard in some areas and an underestimation in others.

There is also an emerging focus for applied economic studies to use iterative adaptation strategies. The main method applied is the “graphical method” of adaptation pathways. Such analysis identifies adaptation strategies in terms of flexibility, but does not answer the question of economically efficient flexibility and timing of adaptation.

Climate cost estimates

A large number of pan-European to national economic studies exist which use integrated sector impact-assessment (I-A), notably using the DIVA coastal model (Hinkel & Klein, 2009). There are also now an increasing number of detailed national and local scale economic assessments. In Europe, recent studies using the integrated assessment DIVA model (in the IMPACT2 and RISES-AM projects) estimate the economic costs from coastal flooding and erosion in the EU are EUR 6 to 19 billion/year for RCP2.6, rising to EUR 7 to 27 billion/year for RCP4.5 and EUR 15 to 65 billion/year for RCP8.5 in the 2060s EU (no adaptation, combined climate and socio-economic change (SSP2), no discounting) (Brown et al, 2016). These costs rise rapidly by the late century, especially for higher emissions pathways. The estimated costs in the EU rise to EUR 18 to 111 billion/year for RCP2.6, EUR 40 to 249 billion/year for RCP4.5 and EUR 153 to 631 billion/year for RCP8.5 by the 2080s.

This indicates a disproportionate increase in costs for higher warming scenarios in the second half of the century, and also highlights the benefits of mitigation strategies. Importantly, there are major differences in the costs borne by different Member States, with the greatest costs projected to occur in France, the UK and the Netherlands (i.e. around the North Sea) if no additional adaptation occurs.

The DIVA model has also been used extensively to look at coastal adaptation and estimate potential costs and benefits. These studies show that adaptation is an extremely cost-effective response, with hard (dike building) and soft (beach nourishment) measures significantly reducing costs down to very low levels. These show it is economically robust to invest in protection. The European adaptation cost estimates are complemented by many national and local studies. Some of these indicate higher adaptation costs, in cases where there are high levels of assets at risk (such as in London) or very high standards of protection (the Netherlands).

These integrated coastal models have also been used to assess high-end sea level scenarios (see tipping points section), which indicate very large increases in economic costs.

Policies and challenges

In 2013, the EU adopted its Adaptation Strategy, which consists in three elements: i) promoting adaptation strategy development and adoption by Member States; ii) “climate-proofing” action at the EU level; and iii) better informing decision-making. Existing studies are useful to inform climate adaptation policy, but due to the limitations mentioned above they do not support adaptation decision making. Decision making in adaptation in the coastal sector faces challenges not tackled by existing studies.

Timing of adaptation: For decision makers the timing of adaptation is important. Immediate adaptation starts to reduce impacts immediately while delayed adaptation can lead to higher impacts in the near future but avoid costly over adaptation as new information will be available in the future. The EU Flood Directive 2007/60/EC, which entered into force on 26 November 2007, requires “Member States to assess if all water courses and coastlines are at risk from flooding, to map the flood extent and assets and humans at risk in these areas and to take adequate and coordinated measures to reduce this flood risk.” It sets out requirements on flood risk assessments, access to information and public participation in planning processes. Further, it specifies that in areas where real risk of flood damage exists, by 2015 flood risk management plans must be drawn up. These plans should be reviewed every six years in a cycle co-ordinated with the EU Water Framework Directive implementation cycle, which adds a time constraint to coastal adaptation. Lin et al. (2014) develop a framework that helps SLR coastal communities identify the trigger point for coastal adaptation. To the best of our knowledge, this is the only study that explicitly targets coastal adaptation planning.

Robust decision making across scenarios: Future sea-levels are uncertain. Climate impact science takes this into account by providing scenarios. Policy makers need to decide across these scenarios, not within single scenarios. With the exception of Lincke & Hinkel (2018) existing studies do not address decision making across multiple scenarios.

Barrier to adaptation: There are barriers that make adaptation difficult. Financial barriers may exist that prevent adaptation projects from being realized even if they are economically efficient. Social barriers in the form of social conflicts caused by competing interests of different stakeholders can also prevent adaptation projects from being realized even if they are economically efficient and sufficient capital can be acquired (Bisaro & Hinkel, 2016; 2018; Hinkel et al., 2018). Existing studies rarely take into account existing barriers or identify possible future barriers. Current research is mostly descriptive. There is a need for further research in the field that looks at how barriers evolve over time (dynamic perspective) and how they persist (Eisenack et al., 2014).

Adaptation decisions involve different aggregation levels: Adaptation measures are usually implemented at the local level, while being decided on subnational or national level and being financed from national or international sources. These different levels are not taken into account in existing climate cost assessments.

Key gaps

While there are further improvements that can be made to the models, such as with local differentiated sea level rise, improved resolution of population and elevation data, and downscaled consideration of major cities and ports, the main gaps relate to the need to integrate adaptation pathways and decision making under uncertainty into the European, and national scale models and strategies. There are also a set of activities to consider the economic, financial and social barriers to adaptation, and to extend the analysis of extreme scenarios to include socio-economic tipping points.

Table 8: Summary of key gaps: Coastal flooding

Summary: Coastal flooding		
Impact / topic	Quantity and quality of information	Key gaps
Impacts		
<i>Coastal flooding - Adaptation strategies and models</i>	<i>Poor</i>	<i>Adaptation is modelled by simple, stylized rules in existing studies.</i>
<i>Subnational coastal population dynamics</i>	<i>Poor</i>	<i>Subnational coastal population dynamics (coast-ward migration/ land-ward migration) not taken into account in existing studies.</i>
<i>Regional SLR patterns</i>	<i>Very Good</i>	<i>Locally different sea-level rise is often not taken into account in impact studies.</i>
<i>Coastal flooding - elevation and population data</i>	<i>Poor</i>	<i>Huge differences in area and population exposure in different available data sets. Differences are most extreme below 1 m elevation.</i>
<i>Flooding tipping points</i>	<i>Poor</i>	<i>Tipping points for coastal flooding and adaptation are not explored in existing studies.</i>
Policy challenges		
<i>Coastal adaptation timing</i>	<i>Poor</i>	<i>Timing is a key issue in coastal adaptation policy but ignored in existing studies.</i>
<i>Robust decision making</i>	<i>Poor</i>	<i>Existing studies assess impacts and possible adaptation measures within scenarios, but policy needs to decide across scenarios.</i>
<i>Adaptation barriers</i>	<i>Moderate</i>	<i>Economic, financial and social barriers to adaptation are not included in existing assessments.</i>

4.5 Energy

Introduction

Temperature is one of the major drivers of energy demand in Europe, affecting summer cooling and winter heating for households and industry and service sectors. Higher temperatures are expected to raise electricity demand for cooling, decrease demand for heating, and to reduce electricity production from thermal power plants (Mideksa & Kallbekken, 2010). These responses are largely autonomous, and can therefore be considered as an impact or an adaptation. It needs to be considered, however, that cooling

is predominantly powered by electricity (which is more expensive), while heating uses a wider mix of energy sources. For estimation of the demand side, further socio-economic drivers and upcoming energy and climate mitigation policy and pathways need to be taken into account.

Climate change will also have effects on energy supply, notably on hydroelectric generation, wind, solar and biomass, but also potentially on thermal power (nuclear and fossil) plants (including use of cooling water and thermal efficiency).

Methods for economic assessment

At the European and national level, there are quantitative impact assessment studies of the likely change in heating and cooling demand. Several methodologies are used to quantify this impact, from bottom-up energy modelling to regression analysis. There are a large number of energy models already in use, including least cost energy modelling and general equilibrium models, as well as studies that use econometric analysis. These can be extended to take account of changes in heating and cooling demand, typically by assessing the impact of climate change on heating and cooling degree days.

Climate cost estimates

There are published studies that provide autonomous adaptation costs for changes on **energy demand**. Mima et al. (2011) assessed the costs of additional cooling for the residential and service sector for Europe, the US, China and India using a least cost-optimisation energy model (i.e. looking at the additional marginal costs of providing extra generation). These indicate large increases in cooling costs: in Europe alone, these were estimated at around EUR 30 billion/year in EU27 by 2050, rising to EUR 109 billion/year by 2100 (A1B scenario). Under the E1 scenario, the total costs of cooling demand due to climate change (alone) were much lower, estimated at approximately EUR 20 billion/year across the period 2050 - 2100. A strong distributional pattern was found, with high net increases in Southern Europe. However, a similar level of economic benefit was projected from the reduction in winter heating demand from warmer temperatures, though with benefits arising in the Northern and North-Western European countries.

Ciscar et al. (2014) estimated in the PESETA II-study that overall EU energy demand (residential and commercial sector) could be reduced by 13%, mainly due to reduced heating requirements. Reductions in energy demand can be expected in all European regions except Southern Europe, where the need for additional cooling would lead to a demand increase of close to 8%. In the 2°C simulation, a lower reduction of EU energy consumption by 7% is estimated.

Some studies highlight a switch in sign over time, with overall heating and cooling demand declining until 2050 and increasing by the end of the century with stronger warming (e.g. Isaac & Van Vuuren, 2009). Recent studies for Europe point to a net zero or a net decline in electricity demand for Europe as a whole, but with increases in the south of Europe (Dowling, 2013; Eskeland et al., 2010; Labriet et al., 2015, Mima & Criqui, 2015; Pilli-Sihvola, 2010; De Cian & Sue Wing, 2017; Wenz et al., 2017). Gas and petroleum product demand generally decline, as the heating effect prevails in residential and commercial buildings. De Cian & Sue Wing (2017) find that natural gas is sensitive to hot temperature and can increase in industry if used for cooling.

For the supply side there are several studies for hydropower generation, wind power generation, solar power and thermal power plants (nuclear and fossil fuel). The main mechanisms through which climate change can affect **hydropower production** are through changes in river flow, evaporation, and dam safety (Mideksa & Kalbekken, 2010). For Europe, most studies show a positive effect for northern Europe and a negative effect for South and Eastern Europe (Hamududu & Killingtveit, 2012; Mideksa and Kalbekken, 2010; Lehner et al., 2005; Van Vliet et al., 2016; Teotónio et al., 2017; Turner et al., 2017). The extent to which climate change affects hydropower in Europe as a whole differs among the studies from almost no effect (Zhou et al., 2018; Hamududu & Killingtveit, 2012) to decreases of 5-10% by the end of the century or before (Lehner et al., 2005; Turner et al., 2017; Chandramowli & Felder, 2014). This difference can be due to several reasons, such as the type of climate model used and because some studies analyze changes in the theoretical potential (which can be very large) while other studies look at changes in generation (which are generally much smaller). Van Vliet et al. (2016) conclude that various adaptation options could offset the overall negative effects in Europe. Climate model uncertainty is mainly addressed in the more recent studies (e.g. Van Vliet et al. 2016; Turner et al., 2017).

Changes in wind patterns as a consequence of climate change can affect wind power generation through increased variability in generation, damages to wind turbines due to extreme weather events, intermittency in generation leading to increased firm backup capacity, and icing on wind turbines (Chandramowli & Felder, 2014; Pryor & Barthelmie, 2010). Results are highly uncertain and characterized by strong seasonality. Carvalho et al. (2017) is one of the few studies that examines the effect of climate change on European wind power resources systematically with different climate models. Tobin et al. (2014) assessed the potential impacts of climate change on wind generation, finding that mean energy yields will reduce by less than 5% by 2050 (2°C scenario). Other studies have focused predominantly on Northern Europe or the UK (Pryor et al., 2005; Cradden, 2010; Hdidouan & Staffel, 2017).

Solar power may be affected by climate change via increasing ambient temperature (leading to lower efficiencies for photovoltaic system but higher for concentrated solar power (CSP) technology, changes to insolation (or cloud cover) and specifically for CSP decreasing water availability (Chandramowli & Felder, 2014; Wild et al., 2017). Existing studies point to higher efficiencies for solar power in Europe, especially for CSP (Wild et al., 2015; 2017; Crook et al., 2011; Bartok, 2010).

Climate change affects thermoelectric power mainly because increased water and air temperature decreases the efficiency of thermal cooling. Existing studies show a decline in power generation in both nuclear and fossil power plants due to efficiency losses and power plant cooling. Most thermoelectric power plants are situated in areas with expected declines in mean annual streamflow combined with strong water temperature increases, which both amplify restrictions on cooling water use (Mima & Criqui, 2015; Van Vliet et al., 2016; Van Vliet et al., 2012). Mima & Criqui (2015) estimated that thermal and nuclear power generation could be reduced by up to 2-3% (thermal) and 4-5% per year (nuclear) for current plant (A1B) though changes in plant design would reduce these significantly. The TopDAd study assessed these impacts for nuclear power in France and estimated losses could vary between tens and several hundred billions of euros per decade by 2100 (for current infrastructure and policies. Adaptation activities can significantly reduce impacts

increased efficiencies, changes in cooling system types and fuel switching (Van Vliet et al., 2016; Kopytko et al., 2011).

Policies and challenges

The main objectives of the Energy Union are to provide secure, affordable, and clean energy for EU citizens and businesses. To achieve this, the Energy Union strategy focuses on i) ensuring energy security, ii) creating a fully integrated internal energy market, iii) improving energy efficiency, iv) decarbonising the economy (not least by using more renewable energy), and v) supporting research, innovation and competitiveness. We focus here on the pillars i), iii), and iv), as these have the strongest interactions with climate change.

Many studies have focused on the challenge of decarbonization the economy, including multi-model comparison studies. A key policy challenge is which changes in the energy system are needed to achieve the Paris Agreement goal. For an overview see Chapter 6 of IPCC AR5 WGIII report (Clarke et al., 2014) and for an overview of energy developments in the SSPs, Bauer et al. (2017). Existing studies have a relatively strong focus on electricity supply, with less detail on industry and heating. For Europe, the Energy Roadmap 2050 (European Commission, 2011) explores the transition of the energy system in ways that would be compatible with a greenhouse gas reductions target of 80-95% by 2050. For the period until 2030, EU countries are developing Integrated National Energy and Climate Plans based on a common template.

To make Europe more climate-resilient, the EU has formulated an Adaptation Strategy (European Commission, 2013a, and specifically for infrastructure European Commission, 2013b), in which it is stressed that future climate conditions have to be taken into account in constructing (energy) infrastructure. Furthermore, the Strategy mentions the importance of a thorough and coherent assessment of local climate impacts to achieve sector- and location specific climate resilience. Finally, the Strategy recommends making climate change assessments and system-wide vulnerability checks for interconnected installations, developing long-term (investment) strategies and incorporating climate issues into planning and maintenance procedures. Regarding specific measures, the Strategy calls for both engineering measures (such as additional cooling circuits for power plants or design standards for distribution poles) as well as non-engineering measures. The latter may include more robust operational and maintenance procedures, better demand management and forecasting or early-warning systems.

Increasing energy efficiency helps to achieve the objectives of decarbonization as well as energy security. Existing policies to improve energy efficiency in Europe include the Directive on Energy Performance of Buildings, the energy labelling of household appliances and office equipment, the Ecodesign Directive, and the Energy Efficiency Directive, which placed an obligation on Member States to achieve energy savings. In 2016, the European Commission published a report about good practices in energy efficiency (European Commission, 2016). Measures to improve energy efficiency in buildings, industry, business, and services, and products are being discussed. Conclusions from this report include: 1) Building refurbishment has the biggest available energy saving potential in Europe; 2) Given the broad scope of the service sector, there is a clear need for targeted energy saving solutions that focus on the individual sectors, 3) The combination of energy labelling and minimum energy performance standards clearly results in energy savings; and 4) Setting an

energy efficiency target is a strong incentive and impetus for triggering additional energy efficiency measures and following up on their delivery.

Key gaps

While there are some studies, a major gap still exists on cooling demand, including extremes and the costs and benefits of adaptation options for cooling. There are gaps remaining also on the economic costs of extremes on hydropower, wind, and thermal generation, and overall energy security.

Table 9: Summary of key gaps: Energy

Summary: Energy		
Impact / topic	Quantity and quality information	Key gaps
Impacts		
Supply side		
<i>Hydropower</i>	<i>Good</i>	<i>Assessment of adaptation options Relation between water availability and actual power generation Effects on overall energy systems</i>
<i>Wind power</i>	<i>Moderate</i>	<i>Few European-wide studies, focus mainly on energetic resources and not on energy system impacts</i>
<i>Solar power production</i>	<i>Moderate</i>	<i>Few European-wide studies, focus mainly on energetic resources and not on energy system impacts</i>
<i>Thermoelectric power:</i>	<i>Good</i>	<i>Effect on individual plants has been studied, but impact on energy system not yet</i>
Demand side		
<i>Cooling and heating demand</i>	<i>Good</i>	<i>Limited research on the interaction between extensive (e.g. expansion in air conditioners, change in building characteristics) and intensive margin (e.g. use of electricity conditional on the demand for appliances). Most analyses focus on the residential sector, with limited research in other sectors (e.g. industry, commercial, agriculture) Most analyses focus on degree days, limited assessment of other climate indicators including extreme weather events.</i>
Policy challenges		
<i>Decarbonizing the European economy</i>	<i>Good</i>	<i>Existing studies have a relatively strong focus on electricity supply, with less detail on industry, heating, and demand.</i>
<i>Increasing energy security</i>	<i>Moderate</i>	<i>In terms of the impacts of climate change on energy security of supply, relatively little research on adaptation options.</i>
<i>Increasing energy efficiency</i>	<i>Moderate</i>	<i>Previous model studies have a relatively simple representation of energy efficiency improvements; only recently model studies have focused on the effect of behavioural change. How to support behavioural change is under-researched.</i>

4.6 Transport

Introduction

Most of the climate change concerns related to the transport sector are tied to the risks of extreme events: flooding, heat waves, droughts and storms, i.e. where climate change leads to exposure that is outside the design range. These risks affect different elements of the transport system: infrastructure, demand (travel time) and accidents. Given the long lifetime of transport infrastructure, climate change is a concern and adaptation has an important role in reducing future risks to this sector. There is also an increasing recognition

that climate change will affect all modes of transport, though in different ways. The European transport system can be subdivided into 1) road; 2) rail; 3) airtravel; 4) inland navigation/marine shipping and 5) intermodal hubs where passengers and cargo are exchanged (airports, harbours, stations, truck terminals).

During the last years, there have been two EU-FP7 projects on impact of climate changes and weather extremes on transport systems: WEATHER and EWENT. In addition, there was a project with a focus on inland waterways networks: ECCONET. The EU-FP7 project ENHANCE studied flood damage to railway infrastructure in the Alpine region as a case study. A comprehensive overview of these projects is given by the EEA (2017).

The WEATHER project summarizes that from the perspective of extreme weather events, roads have the largest share in current overall costs (80%), followed by air (16%) and rail (3%). The net effect of climate change on the road sector remains uncertain, because the costs induced by heat stress and flooding may be outweighed by a strong reduction in winter maintenance costs. The influence on air transport is very uncertain, because most costs are from extreme wind and fog, and there is little agreement about future extreme wind and fog conditions between climate model projections.

For the rail sector, a rapid increase in total costs is expected, mainly due to heat stress (buckling) and increase of heavy rain events (WEATHER, as reported in Doll et al., 2014). Regarding inland waterways, before 2050 no significant changes in low flows are expected. Beyond 2050 this may change into drier summers with lower flows in Rhine and Danube, causing a shift to smaller vessels and a minor shift in modal split, this may lead to an increase price per transported ton by 2071-2100 (EEA, 2017; Bruinsma et al., 2012).

Method for economic assessment

Concerning methods, both projects (WEATHER and EWENT) take their starting point in identifying adverse extreme weather phenomena, for which thresholds are determined beyond which harmful impacts will occur. The change in exceedance of these thresholds due to climate change is monetized via accident costs, delay costs, maintenance costs and infrastructure damage. Infrastructure damages are mainly based on damages of historical events. For maintenance costs, different sources such as statistics are used. The calculation of delay costs is informed by “willingness to pay” studies. A number of studies extend flood risk modeling (detailed earlier) to look at transport related damages, and in some cases, extend these to look at travel time disruption. Analysis of major events can be considered using transport network models, input-output models or using wider economic analysis.

One difficulty in studying the impact on transport infrastructure is that damages reach far beyond the sector itself, so that damages due to network disruptions are found in other sectors. There are very different approaches to calculating infrastructure damages: reasoning from direct costs on infrastructure assets; starting from the frequency of extreme weather events (WEATHER/EWENT) and accounting for accidents and losses of times; studying disturbances freight flows and modal split over multimodal networks; representing transport as disturbances in input-output models of different sectors; or starting from the damage to critical infrastructures, notably hubs in the network.

Climate cost estimates

There are a growing number of studies in this area, across various modes of transport, though it is stressed that climate change has different effects on road, rail, air and water

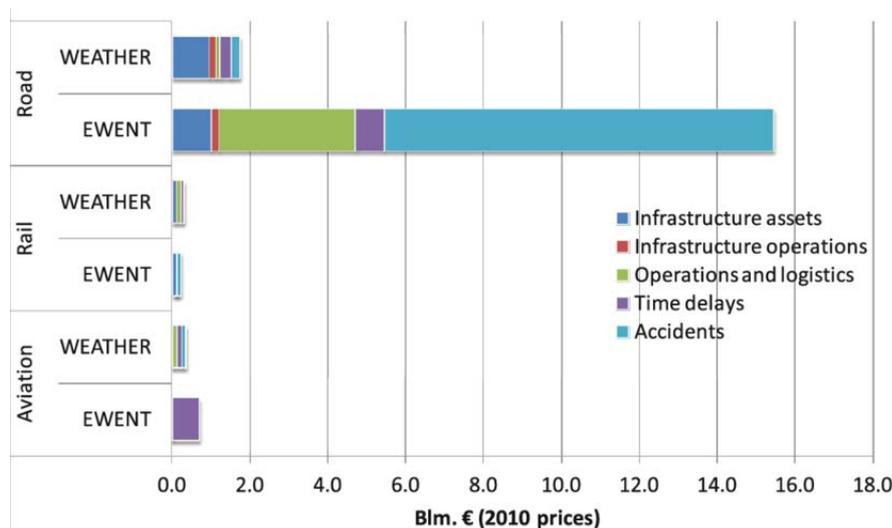
transport, as well as intermodal terminals. The PESETA II study (Ciscar et al., 2014) considered impacts on the road and rail network, estimating the total damages to transport infrastructure due to extreme precipitation at EUR 930 million/year by the end of century under an A1B scenario (a significant increase from the current baseline damage of EUR 629 million/year) and EUR 770 million/year under a 2°C scenario. More specific estimates also exist for road transport. The future costs are driven by future socio-economic assumptions, i.e. on transport patterns and demand.

The WEATHER project assessed total costs from extreme weather events at EU 2.5 billion/year for 1998-2010, and by 2040-2050 an increase of 20% is expected. (Przyluski et al., 2011; EEA, 2017). Road transport comprises the highest share, estimated at EUR 1.8 million/year today, with an increase of 7% estimated for 2040-2050. EUR 306 million/year is assessed for the rail sector (for 2010), a significant increase of 72% is expected for the years 2040-2050.

The EWENT project estimated weather related costs at EUR 18 billion/year in road transport for the baseline 2010. The estimated costs for 2040-2070 are an increase by EUR 2 billion/year (including a large decrease of accident costs due to non-climate reasons such as technical improvements). For rail transport an increase of EUR 117 million/year is projected between 2010 and 2040-2070 (Nokkala et al., 2012).

There is a large discrepancy between the results of WEATHER and EWENT (see also Figure 3); in EWENT, the current total costs due to extreme weather in Europe for the road transport network are six times higher than in WEATHER. The differences were attributed to a stricter definition of extremes in WEATHER, a more complete coverage of weather phenomena in EWENT and a more cautious approach to accounting accident costs in WEATHER (Michaelides et al., 2014). The approach is very sensitive to accounting for losses of life (~EUR 10 billion EWENT) and the decrease in fatalities due to improved road safety conditions.

Figure 3: Total current annual European costs due to extreme weather by mode and study. Source: Michaelides et al. (2014)



The JRC study on critical infrastructure (Forzieri et al., 2018) estimates that multi-hazard, multi-sector damage could increase annual damages in the European³ transport sector from

³ EU28 plus Switzerland, Norway, Iceland

EUR 0.8 billion today to EUR 11.9 billion by 2080s due to effects of climate changes. All European regions are projected to experience an increase, Southern and South-Eastern Europe will see a substantial increase due to droughts and heatwaves, and there are also large impacts in European floodplains and coastal regions.

Policies and challenges

The legal basis for the EU infrastructure adaptation and mitigation is provided by the Trans-European Transport Network (TEN-T). The most recent regulation is guideline 1315/2013, which calls for mitigation and adaptation actions to ensure that core corridors in the EU transport network are resilient towards climate change impacts. Besides this legal basis, the EC prepared staff working document 2013/137 as a strategy to adapting infrastructure to climate change.

Further, the TEN-T programme consists of several EU projects to support adaptation strategies in the member states. The EU-FP7 project MOWE-IT (2012-2014) provided a series of guidelines on operation of transport network under adverse weather conditions. On request of the Conference of European Directors of Roads (CEDR), the ROADAPT project (2012-2015) provided guidelines for adaptation of road infrastructure to climate change for road operators. It built on an earlier risk assessment framework called RIMAROCC developed in 2008-2010. The EU-FP7 project INTACT studied the impact of climate change on critical infrastructures and came up with a set of guidelines for planning and protecting critical infrastructures and preparing for emergency response and recovery. The EU-FP7 project INFRARISK proposed a framework for stress-testing critical parts of the infrastructure system.

On a national level, several EU member states are studying how their road networks can be made more resilient. The Danish Road Institute developed the 'blue spot' approach (ROAD-ERA-NET), as a method to identify vulnerable parts of the highway system to flooding, which was also applied in Sweden and The Netherlands. The Netherlands just started (2018) the project 'climate resilient networks' to improve modelling of pluvial flood risk with the aim of moving from exposure maps to risk maps. The UK carried out elaborate climate change risk assessments in 2012 and 2017, with special attention for risk in transport infrastructure networks (e.g. embankment failures, high temperatures in public transport) identifying increased frequency and severity of flooding as the most significant climate change risk. For Scandinavian countries, higher winter temperatures also have some drawbacks: more frequent temperature-0°C crossing may decrease usability of rural roads and increase frost damage (EEA, 2017).

It was observed that for less-developed areas in Europe, there are serious disruptions of transport infrastructure due to flooding, landslides and earthquakes, which hinder national development and trade. For example, in 2014, flood damages in Serbia added up till 4.7% of GDP and for Bosnia and Herzegovina even 15% (World Bank, 2017). Development banks like the World Bank recognize that climate resilient transport infrastructure is key to the economic resilience of countries and are therefore putting increasing investments in climate proofing infrastructure in less developed countries.

With regard to inland waterways, adaptation measures are very well studied within the ECCONET project and by Deltares, the VU University and Wageningen University (The Netherlands), including adaptation tipping point approaches for river navigation.

With regard to road transport, EC commissioner Clara De La Torre (TRA, 2016) pointed out that the degree of acceptable risk is often not defined. A cost-benefit rationality is often lacking in road management regulations, as can be derived from very different design standards for different European countries.

Key gaps

The main research priorities are to improve the direct cost estimates for road transport and the costs of flooding for rail transport. Further method development is also needed to assess the indirect costs of transport disruption (for rail and road). Other priorities include the economic costs of climate change on critical transport infrastructure, including inland and marine transport hubs, and the analysis of indirect network effects. Further work is also needed to advance cost-benefit analysis for adaptation investment decisions

Table 10: Summary of key gaps: Transport infrastructure

Summary: Transport infrastructure		
Impact / topic	Quantity and quality of information	Key gaps
Impacts		
<i>Road infrastructure</i>	<i>Poor</i>	<i>Large variety in direct costs estimates to road infrastructure, net effect of climate change uncertain</i>
<i>Rail infrastructure</i>	<i>Moderate</i>	<i>Buckling is well-studied and adaptation measures are prepared; coastal and fluvial flooding remain a threat in certain areas</i>
<i>Air</i>	<i>Poor</i>	<i>Climate model projections do not agree on wind and fog conditions</i>
<i>Inland waterways</i>	<i>Good</i>	<i>Well-studied</i>
<i>Marine shipping, ports</i>	<i>Moderate</i>	<i>Part of critical infrastructure (see row below), for this sector mainly mitigation challenges</i>
<i>Transport hubs and other critical infrastructures</i>	<i>Moderate</i>	<i>Analysis on EU-scale are missing</i>
<i>Indirect costs of several transport modes</i>	<i>Moderate</i>	<i>Indirect costs due to transport disruptions unclear</i>
Policy challenges		
<i>Climate risk tolerance levels for road transport</i>	<i>Poor</i>	<i>Climate risk informed targets with cost-benefit rationality</i>
<i>Climate risk in planning processes (for road transport)</i>	<i>Moderate</i>	<i>Guidance on how to integrate climate risks in planning, design and operations of road infrastructure</i>
<i>Regional differences in risk level (road transport infrastructure)</i>	<i>Poor</i>	<i>Assessments of underdeveloped road networks in EU accession countries</i>

4.7 Health

Introduction

There are a number of potential health impacts that could arise from climate change (Smith et al., 2014; McMichael, 2013). Direct impacts include heat-related mortality and morbidity, as well as deaths and injuries from flooding and other extreme events. Indirect effects include those that arise from changes to natural or human systems, including vector-, food- and water-borne diseases, air pollution, occupational health and mental stress. There are a number of other potential indirect health impacts that could arise from climate change, from altered agricultural production and food security (undernutrition) and conflict, etc.

Finally, there are also risks to health infrastructure (including hospitals), the delivery of health services, and indirect effects on critical infrastructure (e.g. water and power supplies) from extreme weather events. While the focus is often on the impacts of climate change and health, there are also some potential direct health benefits (reduction in cold mortality) and strong health co-benefits from mitigation.

In Europe, the primary focus has been on heat-related mortality, especially following the 2003 heat wave. The IPCC Europe Chapter (Kovats et al., 2014) identifies that heat-related deaths and injuries are likely to increase, particularly in Southern Europe (medium confidence), that climate change may change the distribution and seasonal pattern of some human infections, including those transmitted by arthropods (medium confidence), and increase the risk of introduction of new infectious diseases (low confidence). A most recent assessment in Europe was undertaken in the World Health Organization (WHO-Europe) report (2017).

Methods for economic assessment

There are a number of studies that have quantified and valued the impacts of climate change on health in Europe. Results vary with scenario and climate projection, but also with socio-economic assumptions, as the latter affects population growth, health care systems, and the rising proportion of elderly people in Europe. The impacts on health are more difficult to value than other sectors, because there are no observed market prices. However, values are derived by considering the total effect on society's welfare, consisting of three components:

- The resource costs i.e. medical treatment costs;
- The opportunity costs, in terms of lost productivity; and
- Dis-utility i.e. pain or suffering, concern and inconvenience to family, loss of quality of life and others.

The first two components can be captured relatively easily. The third can be derived from estimating the 'willingness to pay' for reducing a particular health risk or health outcome. The WTP values are derived using survey-based stated preference methods and/or "revealed" preferences methods based on observed expenditures such as on consumer safety. A key issue is on the valuation of the change in risk of a fatality, especially for heat and air pollution related mortality, as these predominantly impact those who are old and/or have existing health conditions. There is therefore an issue as to whether to value these groups using the full Value of a Prevented Fatality/Value of a Statistical Life (EUR 1.16 million, 2010 prices) or an adjusted Value of a Life Year combined with the average period of life lost (VOLY of EUR 63,000, 2010 prices). The latter might be seen as the most appropriate specifically for displaced mortality (Chiabai et al., 2018). The state-of-the-art, however, recommends a VSL approach (OECD, 2012). Recent assessments of health and climate for Europe were undertaken as part of the IPCC Europe Chapter (Kovats et al., 2014) and the World Health Organization (WHO-Europe) report (2017).

Climate cost estimates

Heat-related mortality and morbidity including heat extremes. Climate change will have impacts on heat related mortality and morbidity in Europe. There are several EU wide estimates of these economic costs (Watkiss & Hunt, 2012; Kovats, 2011; Paci, 2014;

IMPACT2C, 2015) and also studies at the Member State level. The most recent estimates in Europe (Kendrovski et al., 2017) found impacts to be EUR 11 to 41 billion/year by the middle of the century for a 2°C scenario (RCP4.5, climate and socio-economic impact, no adaptation, current prices, undiscounted), with two-thirds of the increase due to the climate signal, and the other third being attributed to demographic change. The largest impacts were found in the Mediterranean, and some Eastern European countries. Costs rose strongly in later years with higher warming. Several studies show costs vary strongly according to whether future acclimatization is included, and on the metric used for valuation (VSL or VOLY). European wide studies do not yet take account of existing European heat alert systems, and thus overestimate impacts, though localized analysis has been made of the benefits and costs of these systems (Hunt et al., 2016; Chiabai et al., 2018; Bouwer et al., 2018). There is also a question of whether the existing studies fully capture heat waves and heat island effects. Results do not include heat related morbidity, but in terms of overall costs, these are thought likely to be low.

Cold related mortality and morbidity. Climate change is likely to reduce future cold-related mortality. Studies that have assessed these (Watkiss & Hunt, 2012) find that cold-related benefits are at least as large as heat related impacts for Europe.

Food-borne disease. Salmonellosis is an important cause of food-borne illness in Europe and is sensitive to ambient temperature. Earlier estimates of costs (Kovats et al., 2011) estimated welfare costs at EUR 36 million/year in the 2020s (A1B), rising to EUR 68 million/year and EUR 89 million/year in the 2050s and 2080s respectively - but falling to EUR 30, 46 and 49 million/year if a decline in incidence due to better regulation is included. A latter study (Paci, 2014) estimated resource costs for hospital admissions and salmonellosis and campylobacteriosis at EUR 700 million in 2041-2070 (A1B).

Labour productivity and occupational health. Climate change will have negative impacts on labour productivity, as work rates decline with rising heat and humidity. Earlier studies estimated effects were modest in Europe for outdoor work. Kovats et al. (2011) estimated that Southern Europe would incur a mean loss of productivity – measured as days lost - of 0.4% to 0.9% by the 2080s (A1B) with total productivity losses for Europe at EUR 300 - 740 million. Recent updates (Lloyd et al., 2016) assess productivity loss for three sectors: agriculture, industry, and service. They estimate 0.4% lost productivity for southern Europe (2050s) with a 0.2% loss for central Europe.

Risks of extreme events, including mental stress. There are risks of fatalities and injuries from extreme events, i.e. coastal storms and flooding, river flooding and storms. The impacts were estimated for coastal events in Europe (Kovats et al., 2011) with welfare costs at EUR 151 million/year in the 2050s and EUR 750 million/year by the 2080s. These fall significantly under the E1 mitigation scenario and fell very dramatically with coastal adaptation. There are fewer estimates of the health impacts of river flooding and storms from climate change, though some national estimates exist. There are also potential impacts on well-being, with higher reported incidence of mental illness in those affected. Country level (UK) analyses (Hunt & Watkiss, 2012) indicate these costs are low when compared to other categories. There are also potential indirect impacts from drought, related to nutrition and water. Heavy rainfall may sometimes result in infectious disease outbreaks (leptospirosis).

Vector-borne disease. These refer to infections transmitted by the bite of blood-sucking arthropods such as mosquitoes or ticks. These species are sensitive to climatic factors, and climate change has the potential to change prevalence (range) and occurrence. In Europe, tick-borne diseases are currently most important (Tick-borne encephalitis (TBE) and Lyme disease). There are some estimates of impacts and studies of the WTP for vaccination against tick-borne encephalitis (Slunge, 2015). There are risks of mosquito borne disease increasing (or re-emerging in Europe), notably malaria, dengue fever and Chikungunya, but risks are low because of effective vector control measures. In the longer-term, there is the potential for expansion of other vectors or parasites responsible for disease into Europe.

Water-borne disease. The impacts of water borne disease primarily arise from extremes (floods and droughts) affecting water quality and availability. They are highly site-specific and involve indirect pathways, and thus are not well assessed at European level (though there are country studies). These do not find large health impacts, but they do highlight that the costs of additional water treatment could be high.

Air pollution including mitigation co-benefits. Climate change will change the concentrations of ozone and particulate matter, affecting health impacts from air pollution. These impacts were assessed in the IMPACT2C project. For ozone, models predict an average increase across Southern and Central Europe but economic costs were low. For particulate matter, changes due to climate change were found to be very uncertain, as the models did not agree on sign, but impacts/benefits could potentially be several billion Euros per year. Much larger economic benefits arise from mitigation policy, in terms of the positive co-benefits on health from reduced pollution (e.g. Ščasný et al., 2015). The European Clear Air Package (European Commission, 2013), is estimated to avoid 58,000 premature deaths, with benefits of around EUR 40-140 billion.

A further risk is from changes in aeroallergens. Climate change is likely to trigger changes in pollen concentration, volume and distribution, with an associated change in the prevalence and severity of allergic diseases in many parts of Europe. There are no estimates of these impacts and thus no valuation estimates. This could be a potentially large impact and represents a major gap.

Health infrastructure and health services. There is emerging information, at the national level, on the potential impacts of climate change on health infrastructure and health service delivery, from national level down to local level (including all services, including social care). This, though, remains an important gap in the knowledge base.

Tipping points. There are also some potential health tipping points, though most of these relate initially to other sectors (e.g. high SLR, food insecurity). There are, however, human bio-physical limits (wet-bulb temperature) (Sherwood & Huber, 2010).

Macroeconomic health impact assessment. Health impacts can only be partially captured in economic modelling assessments, because of non-market impacts. However, CGE models now include effects of morbidity on labour productivity and resource costs. The Circle analysis (OECD, 2015) used such an approach for morbidity from heat and cold, as well as infectious diseases, respiratory illnesses, and occupational heat stress, though found the total impacts were low for Europe. The PESETA II project (Ciscar et al., 2014) also included heat related impacts (welfare losses) and occupational productivity losses. They report very large health impacts (2/3 of all welfare losses). More recent analysis has been undertaken by Bosello et al. in the BASE project (2018).

Policies and challenges

The most recent assessment of policy needs in Europe was undertaken in the World Health Organization (WHO-Europe) report (2017). This identified several challenges including: heat in cities, as well as other extreme events; distributional differences in health-related impacts across Europe and cross sectoral policy linkages, i.e. the need to include health in responses for coastal, river floods, water policy, etc. This latter challenge is important as in many cases, adaptation will take place in these sectors, rather than through health sector policy.

Heat issues were also highlighted in the recent RAMSES cities study (<http://www.ramses-cities.eu/home/>) and JRC critical infrastructure reports, due to the projected increased frequency of heat waves in Europe in the late 21st century.

In terms of EC policy, Health 2020 includes priority areas that specifically relate to protecting health from climate change⁴. There was also a 2013 initiative Climate, Environment and Health Action Plan and Information System (CEHAPIS) between the EC and WHO. More recently, the Sixth Ministerial Conference on Environment and Health (2017⁵) also set the objective regarding climate change and health of strengthening adaptive capacity and resilience to climate change-related health risks and supporting measures to mitigate climate change and achieve health co-benefits in line with the Paris Agreement. This included a proposed action to ‘Support research on the effectiveness, cost and economic implications of climate change and health interventions, with a particular focus on mutual co-benefits (WHO Europe, 2017).

The European Centre for Disease Prevention and Control also has a theme on climate change⁶. It has assessed the effects of climate change on infectious diseases and has established a pan-EU network dedicated to vector surveillance (ECDC, 2012). This highlights that health systems must prepare for - and respond to - potential new disease outbreaks.

While there is a strong role for Europe, especially on disease transmission, much of health policy and services implemented by Member States are delivered at the devolved administration level, noting that health systems vary in Europe. Similarly, most adaptation responses are local, for example heat alert systems are often set up at the city scale.

Many of the policy documents highlight the high health benefits of mitigation (primarily from air pollution improvements). This is important for mitigation analysis in the project.

Key gaps

The review shows there is reasonable coverage of economic costs, covering slow onset and some extremes. However, there are a large number of gaps. To date, most focus has been on heat related mortality, though important issues remain in this area with regard to valuation, distributional impacts (between north and south), hot-spots and adaptation strategies. There are key gaps in relation to vector borne disease and aeroallergens, a need to understand the potential impacts on health services and social care, and to consider possible health tipping points.

⁴ tackling the Region’s major health challenges of noncommunicable and communicable diseases; strengthening people-centred health systems, public health capacity and emergency preparedness, surveillance and response; creating resilient communities and supportive environments.

⁵ <http://www.euro.who.int/en/media-centre/events/events/2017/06/sixth-ministerial-conference-on-environment-and-health>

⁶ <https://ecdc.europa.eu/en/climate-change>

Table 11: Summary of key gaps: Health

Summary: Health		
Impact / topic	Quantity and quality of information	Key gaps
Impacts		
<i>Heat related mortality and morbidity</i>	<i>Moderate</i>	<i>Effects of heat waves and Urban heat island Valuation mortality (including period of life lost) Acclimatisation Effects of adaptation Morbidity impacts</i>
<i>Cold related mortality and morbidity</i>	<i>Poor</i>	<i>Mortality and morbidity impacts and valuation</i>
<i>Food-borne diseases</i>	<i>Moderate</i>	<i>Beyond salmonellosis</i>
<i>Vector-borne diseases</i>	<i>Poor</i>	<i>Tick borne disease in Europe New vector surprises</i>
<i>Water borne disease</i>	<i>Poor</i>	<i>All water borne disease</i>
<i>Fatalities and injuries from extremes (floods, storms)</i>	<i>Poor</i>	<i>Surface water and storm fatality and injuries</i>
<i>Mental health</i>	<i>Poor</i>	<i>Mental health related to flooding extremes</i>
<i>Air pollution</i>	<i>Moderate</i>	<i>Effects on particular pollution</i>
<i>Allergens</i>	<i>Poor</i>	<i>Allergy impacts (aero allergens) such as pollen</i>
<i>Air pollution co-benefits of mitigation</i>	<i>Good</i>	<i>Covered by other projects</i>
<i>Labour productivity and occupational health</i>	<i>Moderate</i>	
<i>Health infrastructure and health services</i>	<i>Poor</i>	<i>Impacts on health infrastructure and health services incl. social care</i>
<i>Macro-economic analysis</i>	<i>Poor</i>	<i>Updated macro estimates Distributional effects</i>
Policy challenges		
<i>Heat waves and health</i>	<i>Moderate</i>	<i>Heatwave and UHI Distributional effects Adaptation policy</i>
<i>Cross cutting inclusion of health in other areas</i>	<i>Poor</i>	<i>Inclusion of health adaptation/co-benefits in other sector analysis</i>
<i>Health adaptation</i>	<i>Poor</i>	<i>Costs and benefits of health adaptation</i>
<i>Distributional impacts across Europe, and within groups</i>	<i>Moderate</i>	
<i>Health tipping points</i>	<i>Poor</i>	<i>Health impact of tipping points Health specific tipping points (extreme heat, wet bulb)</i>

4.8 Tourism

Introduction

Globally, the tourism sector is of enormous importance (9% of global GDP) and is highly dependent on climatic factors (Roselló-Nadal, 2014). While the overall demand for tourism will continue to increase over the next few decades, the distribution, timing, and type is expected to shift as a result of climate change (Ciscar et al., 2009; Aaheim et al., 2013). The peak of mass summer tourism in Europe is focused on the Mediterranean where the sector accounts for over 10% of GDP in Spain, Greece and Malta and for over 20% of total

employment in Greece (Aaheim et al., 2009; Bank of Greece, 2011). Increasing temperatures, heat waves and limited water availability may all have negative effects for summer tourism in this region, leading to a shift towards the more comfortable climate of the shoulder period (i.e. Autumn and Spring) (EEA, 2007; Isoard et al., 2008; Kovats & Valentini, 2014; ToPDAd, 2015). Coastline retreat and the impacts of sea level rise may reduce beach coverage and coastal recreation and have important socio-economic consequences for population, infrastructure and assets (Nicholls et al., 2011; Enríquez et al., 2017). Climatic change is also expected to create a strong re-distribution of tourism (and expenditures) from southern to northern Europe (Amelung & Moreno, 2009; Perrels et al., 2015).

For winter tourism, changes in snow availability, cloudiness and wind speed will impact the length and quality of the season, as well as the economic viability of some resorts. Ski resorts at lower altitudes are particularly at risk and this could lead to adaptation costs (artificial snow or extension to higher mountain resorts, changes in choice of destination and timing of visits (Mathis et al., 2003; Prettenthaler et al., 2015; Perrels et al., 2015). The number of snow-reliable skiing areas in the Alps is projected to drop from 600 to 200, depending on the climate scenario (OECD, 2007). In some cases, changing winter conditions could be offset by extended summer alpine tourism, water sports and other outdoor activities (Balbi, 2012). While there are fewer studies examining the impacts of climate change in the Pyrenees, the 98% of resorts that currently have reliable snow would drop to 44% under a +2°C scenario and to as far as 7% under a +4°C scenario (Pons et al., 2015). Increased temperatures in the Balkan region will have negative impacts on winter tourism numbers and expenditure and increase pressures through concentrations of activity in smaller sensitive areas (Prettenthaler & Köberl, 2010; Alfthan et al., 2015).

Methods for economic assessment

Quantitative evaluation of climate change effects on tourism consist of three main categories: physical changes; climate indexes; and tourism demand modelling based on revealed preferences. Numerous studies have assessed the potential effects of climate change on the tourism sector using the Tourism Climate Index (TCI) and cost the changes using tourism expenditure. At present, the Mediterranean has the optimum TCI for summer tourism whilst major source regions (i.e. Northern Europe) do not, although here the TCI is expected to improve. Approaches to model economic costs include a partial adjustment model (i.e. a specific form of the general autoregressive distributed lag (ADL) model) on a monthly basis (Damm et al., 2017), hedonic price model (Barrios & Ibañez Rivas, 2013), an integrated macroeconomic general equilibrium model (Aaheim et al., 2009) and a general circulation model (IMPACT2C, 2015).

Climate cost estimates

Regarding **summer tourism**, several recent studies have used econometric approaches and economic modelling approaches to identify the economic impacts of climate change on tourism (Barrios & Ibañez Rivas, 2013; Ciscar et al., 2014; Rosselló-Nadal, 2014; Perrels et al., 2015). As an example, the PESETA II study (Ciscar et al., 2014) used an econometric analysis, reporting estimated costs of EUR 15 billion/year by the end of the century. Estimates are heavily influenced by assumptions about changes in global tourism, and the underlying global growth in tourism, as well as the autonomous adaptation response of tourists.

Regional tourism revenues from beach summer tourism could oscillate in Europe by -4% to +7% between 2015-2045 due to changes in preferred holiday destinations (Perrels et al., 2015). The regional PESETA II study (Barrios & Ibañez Rivas, 2013) reviewed the economic impacts of climate change to the EU's tourism sector to 2100 focusing on summer tourism and using a travel cost approach and hedonic valuation of recreational demand and related amenities. The study found that climate change would decrease tourism revenues by 0.31% to 0.45% of GDP per year in southern Europe. Other EU countries, in particular the British Isles and northern European regions, are expected to see positive tourism impacts under climate change. Hamilton & Tol (2007) used the Hamburg Tourism Model to examine departures and arrivals, also showing after an initial drop, the number of international arrivals to Germany and the UK would begin to increase around 2030. Barrios & Ibañez Rivas (2013) estimated an annual increase of 0.29% of GDP for northern European regions and a gain of 0.32% for the British Isles. Summer tourism in central European regions shows more moderate changes, varying from losses of 0.16% of GDP to gains of 0.13% of GDP (Barrios & Ibañez Rivas, 2013). Baltic regions are expected to benefit from climate change with an increase in tourism ranging from 1.3-8%, where senior tourists and nature tourists may prefer Northern Europe (Küle et al., 2013).

There are a number of studies that look at **winter tourism**, examining reductions in snow-reliable ski areas (e.g. Pretenthaler & Köberl, 2010; Alfthan et al., 2015). Some also assess the costs of adaptation e.g. costs of additional and increased use of snow machines and extension of ski areas to higher elevations (OECD, 2007). However, very few carry out economic cost estimates for snow-based tourism. For alpine skiing in Sweden, economic losses were estimated by Moen & Fredman (2007) to be in the range of 946.5 to 1755.3 million SEK (EUR 91-169 million) based on a static and linear relationship between projected future days with snowfall, ski-season lengths, and visitor expenditures. Bigano & Bosello (2007) applied different climate change scenarios and related decreases in snow cover, finding the expected average reduction in income from winter tourism to be 10.2% in 2030 and 10.8% in 2090 for Italy. If the 2030 scenario of snow-cover had been experienced in the Italian Alps in 2006, the Veneto and Trentino Alto Adige regions would have seen losses of EUR 2.4 million, and EUR 587 million respectively (Carraro & Sgobbi, 2008). Under a scenario of +2°C, Damm et al. (2017) estimate the maximum weather-induced risk of losses in winter overnight stays in Europe at up to EUR 780 million/season. Projections of actual changes, and the economic implications, are much harder to assess. Much will depend on the flexibility of tourists and institutions such as school holidays

Policies and challenges

The EU is only mandated to support, coordinate or supplement the actions of Member States in the field of tourism and as such policy in this area is rather limited (Juul, 2015). There is little reference to climate change impacts and adaptation. Regarding sustainable tourism, the European Commission has identified diversification, co-funding of sustainable products, indicators for sustainable management; and cycling routes as potential strategies (COM, 2010). The EU's Blue Growth Strategy identifies coastal and maritime tourism as an area with special potential although there is no reference to how this will be affected by climate change (COM, 2014).

The challenges to adaptation in the tourism sector can be divided into 'supply' and 'demand' (Balbi, 2012; ToPDAd, 2015; Barrios & Ibañez Rivas, 2013; Aaheim et al., 2013). On the demand side this includes changes and volatility of demand (EEA, 2007; Aaheim et al.,

2013; Barrios & Ibañez Rivas, 2013). On the supply side, challenges are both technological (e.g. snow making, heating/cooling systems) (EEA, 2007; van Ierland et al., 2007; losard et al., 2008; Balbi, 2012; Aaheim et al., 2013; ToPDAd, 2015) and behavioural (e.g. operational practices, and diversification of activities) (Agrawala & Fankhauser, 2008; losard et al., 2008; Aaheim et al., 2013; ToPDAd, 2015). Few cost estimates of adaptation measures exist and most are in relation to technological adaptations, especially for artificial snow-making (e.g. CEPS & ZEW, 2010; Agrawala et al. 2011). As tourism is a highly subsidised economic sector, public funding at all levels will need to take into account the sector's needs to develop its resiliency and sustainability, including investments in infrastructure (e.g. hiking and cycling trails, beach facilities, roads and access points, etc.) (Balbi, 2012).

Key gaps

There has been a focus on summer beach tourism to date, though there are still gaps, such as the integration of multiple climate impacts (productivity, coastal impacts, water) alongside temperature. There is a major gap for other tourism sectors, with further development for winter tourism and new analysis for nature based and other tourism types. There is also further analysis needed for more analysis of adaptation strategies and costs.

Table 12: Summary of key gaps: Tourism

Summary: Tourism		
Impact / topic	Quantity and quality of information	Key gaps
Impacts		
<i>Summer tourism</i>	<i>Good</i>	<i>Focus on Mediteranean, less information on other destinations and activities and how this may offset winter tourism in some areas e.g. summer activities in Alpine regions. Low level of information on coastal erosion or sea level rise.</i>
<i>Winter tourism</i>	<i>Good</i>	<i>Focus on Alps, less information on other regions and other non snow-based activites e.g. nature or glacier tours. Better snow models needed. Less information available for non-Alpine regions.</i>
<i>Nature tourism</i>	<i>Poor</i>	<i>Lack of consideration of climate change's ecological impacts and their relation to tourism. For example, the ecosystem services offered by biodiversity do not appear in any studies reviewed.</i>
<i>Cruise tourism</i>	<i>Poor</i>	<i>Not mentioned in the reviewed literature, but can have serious implications for shifts in tourism destinations. This is especially the case for an increase in Arctic tourism and reductions in Mediterranean trips.</i>
Policy challenges		
<i>Changes in tourism destinations</i>	<i>Good</i>	<i>Model uncertainties regarding the expected seasonal changes in tourism destinations and severity of such changes. Though many models agree that there will be a shift from Mediterranean areas to Norther European areas- there is little discussion on whether Europe will remain a tourism destination in comparison to other world regions.</i>
<i>Change in demand for tourism activities</i>	<i>Good</i>	<i>Model uncertainties regarding how tourism destinations will adapt and offer alternative activities under climate change, and how these new activities will be attractive to travellers.</i>
<i>Cost estimates of climate change adaptation measures</i>	<i>Moderate</i>	<i>Lack of information and data on the cost of adaptation options for the tourism sector under climate change, especially for tourism types not related to Alpine skiing.</i>
<i>Water management</i>	<i>Poor</i>	<i>Need for improved guidelines regarding water management, especially in conjunction with planned adaptation measures (e.g. snow making) as well as to plan water availability for drinking and recreational purposes</i>
<i>Energy management</i>	<i>Poor</i>	<i>Need for improved guidelines regarding energy management,</i>

		<i>especially in conjunction with planned adaptation measures (e.g. snow making) as well as demand from tourists due to climate warming (e.g. air conditioning)</i>
<i>Infrastructure management</i>	<i>Poor</i>	<i>Lack of revised regulations and guidelines for the design of infrastructure to better include climate resilience and adapt to climate pressures</i>

4.9 Biodiversity

Introduction

Climate change poses a potentially large set of risks to terrestrial, aquatic and marine biodiversity and the ecosystem services they provide (provisioning, regulating, cultural and supporting services). It will shift geographic ranges, seasonal activities, migration patterns, abundances, and species interactions, and has the potential to increase the rate of species extinction in the second half of the 21st century (Settele et al., 2014).

Impacts of observed and projected climate change on terrestrial ecosystems include changes in soil conditions, phenology, species distribution, species interactions, species composition in communities and genetic variability (Lindner, et al., 2010) (slow onset).

As well as terrestrial ecosystems, it is important to note there are potentially large climate impacts on ecosystems from ocean acidification, ocean warming and sea-level rise, as well as freshwater ecosystems (rivers and lakes).

Method for economic assessment

This remains one of the most challenging areas for monetisation since the majority of the impacts on biodiversity are regarded as not being captured by market prices. Consequently, non-market measures of the willingness to pay to avoid adverse impacts – or for positive impacts – are judged to be the most comprehensive in capturing effects on economic welfare. In practical terms, non-market measures of value are not straightforward, or cheap, to obtain, relying either on survey-based evidence or data that captures people’s values through their behaviour (e.g. expenditures made to visit a national park). There is also the possibility that the change in biodiversity results in non-marginal valuation. However, there is some literature on the economic values associated with biodiversity that has been assembled by international initiatives such as The Economics of Ecosystems and Biodiversity (TEEB, 2009; TEEB, 2010).

Climate cost estimates

Impact cost studies are very rare at the European and national levels, though methodological guidance exists (Rodriguez-Labajos, 2013). An exception is the study by Tietjen et al. (2010) that used the Lund-Potsdam-Jena Dynamic Global Vegetation Model for managed Land (LPJmL) (Sitch, Smith et al., 2003; Gerten, Schaphoff et al., 2004; Bondeau, Smith et al., 2007), which simulates the dynamics of both natural and managed vegetation grouped into plant functional types, 2100 under the A1B and E1 SRES scenarios. The authors then mapped existing Willingness To Pay (WTP) results available from the published literature – gathered in the TEEB database (McVittie & Hussain, 2013) - on to the changes in ecosystem services identified from application of the vegetation model. It was therefore essentially a partial equilibrium ecosystem-economic modelling exercise. The simulation

results describe the impact of climate change on potential natural vegetation, i.e. how ecosystems would change without anthropogenic land use such as agricultural production.

Table 13 presents the totals resulting from the use of the unit values in the low end of the WTP value ranges, assuming natural fires exist. The signs of the monetary totals for each biome reflect the physical changes in biome coverage identified in the previous section. Thus, a negative value reflects the fact that there is a projected decline in the area covered by the biome in the EU in the particular time period. From the table it can be seen that both desert & tundra and scrubland would decrease in coverage in the EU in all three time periods in the A1B climate scenario, whilst mixed forests and grassland are positive. Boreal forest, however, is negative at first and becomes positive at the end of the 21st century. Overall, the monetary totals in each scenario are positive, suggesting that the changes in biome coverage projected for Europe have a net positive welfare value.

Table 13: Monetary valuation of Biome changes in EU from climate change (Low range values, €m, 2010). Source: Tietjen et al. (2010)

A1b	2011-2040	2041-2070	2071-2100
desert/tundra	-368	-1,256	-1,321
mixed forest	838	1,160	1,617
boreal forest	-214	-174	179
temperate forest	111	369	509
Scrubland	-267	-471	-824
Grassland	492	920	1,396
Total	591	547	1,555
E1	2011-2040	2041-2070	2071-2100
desert/tundra	173	-108	108
mixed forest	541	774	472
boreal forest	-98	140	307
temperate forest	307	435	49
Scrubland	-310	-526	-325
Grassland	793	1,142	603
Total	1,405	1,856	1,214

Additionally, a study by Hanewinkel et al. (2013) estimated the economic impact of projected climate change for a wide range of temperature increases (between 1.4 and 5.8°C until 2100), using a high-resolution model that predicted presence or absence for 32 tree species under different climate projections (A1B, B2 and A1F1) in Europe. They found that the expected value of European forestland will decrease owing to the decline of economically valuable species in the absence of effective counter-measures. Depending on the interest rate and climate scenario applied, this loss varies between 14 and 50% (mean: 28% for an interest rate of 2%) of the present value of forestland in Europe, excluding Russia, and may total several hundred billion Euros.

Using a contrasting, macro-economic modelling approach, Palatnik & Nunes (2014) examined the climate-change-induced impacts on biodiversity in the agricultural sector in terms of changes in agricultural land productivity. Using a CGE model, the authors found that monetary changes varied significantly across the different European countries. In the case of Mediterranean Europe, initial negative impacts were eventually turned into gains as

a result of the improvement in terms of trade outweighing the initial negative effects. In addition, the estimation results showed that, while developed Western regions in Europe lose slightly, or even gain as in the case of Central and Northern Europe, developing regions in Southern Europe may lose considerably more.

National studies include Berry & Hunt (2006) in the UK which relied on a replacement cost approach to value changes in habitat coverage. A combination of literature review and SPECIES model outputs was used to identify species and habitats of national and regional significance, sensitive to climate change, including some which have a direct economic value. The SPECIES model simulated changes in suitable climate space at the national scale. It was run using A1F1 and B2 high and low emission scenarios. The study used the restoration and re-creation cost data from the UK Biodiversity Action Plan (UK BAP), which were calculated by multiplying the estimates of the area degraded or lost by the annual costs. The results show GBP 360,000 to 816,000 (2004 prices) for the 2020s and GBP 1.4 million to 2.5 million in the 2050s.

By way of further comparison, OECD (2015) undertook an assessment of the global economic consequences of climate change, with regional disaggregation. They modelled changes in terrestrial mean species abundance as an indicator of biodiversity between 2010 and 2050. In order to value biodiversity loss, they adopted a function that relates expenditure on environmental protection to temperature change under climate scenarios. The two climate scenarios adopted were RCP6.0 and RCP8.5. The cost estimates for EU countries under these scenarios were 0.5% of GDP, and 1.1% of GDP, respectively.

The analysis of climate change impacts on ecosystems has increasingly recognized that climate change should be analysed in combination with other drivers of change such as habitat change, invasive species and other forms of pollution, and these changes need to be accounted for in new modelling (EEA, 2017). Mean Species Abundance indicator accounts for the impacts of land use, climate change, eutrophication, infrastructure, and human encroachment on biodiversity. The monetary valuation will use willingness to pay transfer values, rather than the avoidance cost measure which constitutes a minimum value only.

Policies and challenges

The adoption by the European Parliament of the EC mid-term Review of the EU Biodiversity Strategy highlights the importance of accounting for climate change in future assessments of the natural environment, and across all relevant legislation (e.g. updating of Natura 2000, the Habitats Directive and the Water Framework Directive (European Parliament, 2016). It also emphasises the important role of monetising the welfare effects of ecosystem change, as part of a broader move towards more comprehensive measures of economic welfare than GDP. Upcoming work could inform the design of the updating of the EU Biodiversity Strategy. The next iteration of the EU Biodiversity Strategy is planned for 2020/21.

Three main challenges can be described, (1) design and adjustment of adaptation strategies and practices to maintain biodiversity regarding climate change risks, (2) consideration of potential impact of adaptation actions on biodiversity and (3) use of ecosystem based adaptation (Convention on Biological Diversity, 2009). In the EU Adaptation Strategy (European Commission, 2013) and also one of the main recommendations from the supporting studies to the evaluation of the EU Adaptation Strategy in 2017 (Smithers et al., 2017) is ecosystem-based adaptation. This is an important approach for achieving multiple benefits and synergies between biodiversity and ecosystem conservation, socio-economic

development and climate change adaptation. The Convention on Biological Diversity (CBD) defined ecosystem based adaptation as “the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change” (Convention on Biological Diversity, 2009).

Key gaps

There are very large gaps in this field, starting with estimates of physical impacts, and including all aspects of the economic valuation of biodiversity and ecosystem services. More underlying work is needed to understand risk at the spatial disaggregated level across Europe, and to develop WTP estimates. There is also a need to include climate alongside other drivers of change. A final issue is the consideration of possible non-marginal impacts and tipping points.

Table 14: Summary of key gaps: Biodiversity and ecosystem services

Summary: Biodiversity and ecosystem services		
Impact / topic	Quantity and quality of information	Key gaps
<i>Physical risks</i>	<i>Poor</i>	<i>Comprehensive and understandable coverage of risks to biodiversity at EU and national scales Spatially disaggregated estimates of biodiversity impacts across Europe</i>
<i>Monetisation</i>	<i>Poor</i>	<i>Comprehensive measures of WTP and exploration of possible non-marginal impacts.</i>

4.10 Business, Industry and Trade, including Insurance sector

Introduction

One sector that has seen limited covered in the past – and remains so – is the area of business and industry. Climate change has widespread impacts on industry, particularly when taking account of global supply chains (Lühr et al. 2014; BSR, 2015). Relevant biophysical impacts include gradual changes such as sea level rise, increasing temperature and changes in precipitation, as well as extreme events, mainly coastal and fluvial flooding as described above. These are most likely to affect organisations located in areas at risk of extremes (such as flood risks), or those whose activities are closely linked with climate-sensitive resources (such as agricultural and forest product industries, water demands and tourism). This may lead to an increased risk for buildings and production assets, further needs in insurances and increased related financial costs. Water scarcity is likely to increase the difficulty and cost of using water resources, with important consequences for resource-intensive industries such as food and paper industries in affected regions.

In addition to the direct impacts on industry (destruction of construction sites, increased demand for cooling activities and disruptions of supply chains), climate change also leads to indirect effects through the channel of international trade. With a large share of raw materials and intermediate goods imported from climate-sensitive countries and a significant share of final goods exported, European industry will be affected by climate change and its potential effects on costs to businesses, on competitiveness, employment and wider economic performance, even if direct impacts are comparatively small. There are

also the wider issues for the financial service and insurance sectors. The impact of climate change is not evenly distributed among European economies. According to the EEA (2017, p.288) “small, open and highly developed European economies are regarded as particularly vulnerable to shocks in the flow of non-agricultural commodities”.

Climate change impacts on industry can be grouped into three fields: supply chain and procurement risks; impacts on production processes and management; and changes in export markets.

While climate change will affect all aspects of businesses, there has been a particular focus on **insurance**, because it is climate sensitive and because it has a role in supporting adaptation to extreme events. Europe has an extremely complicated and variable insurance system, with very different models among Member States (Porrini & Schwarze, 2014; Schwarze & Wagner, 2009) and thus the impacts of climate change are heterogeneous. The insurance sector, which offers protection against potential losses to assets and crops, is strongly being looked at for offering solutions for building resilience against extreme weather events in terms of providing financial cover and incentivizing climate risk reduction. Projected increase in the occurrence and intensity of extreme weather events will challenge national insurance systems and global reinsurance, which may lead to increases in insurance premiums and decreases in coverage (Lamond & Penning-Rowsell, 2014). However, these effects will be determined by whether there are risk-reducing measures by Governments or insurance customers, as well as by the action of insurers (e.g. in terms of geographical insurance differentials based on risk), noting these may be linked (risk-commensurate insurance premiums). At the pan-European level there are potentially important issues for the European Solidarity Fund. Across all these areas, there is an issue of moral hazard (Arent et al., 2014).

Methods for economic assessment

The research field on impacts of climate change on industry and especially via international trade is just evolving. Nevertheless, four distinct approaches can be identified in the literature: (i) qualitative assessments, (ii) indicator-based assessments, (iii) supply chain risk assessments and (iv) macroeconomic assessments.

Several qualitative studies (i) have been developed on national and company level, e.g. Finland (Kankaanpää & Carter, 2007), Switzerland (INFRAS, Ecologic & Rütter, 2007) and Netherlands (Vonk et al., 2015). The indicator-based assessments (ii) usually build on past information of different indicators, single observations or time series. Indicators are often expressed as ratios to allow for comparison between countries and calculations are needed in order to provide a consistent ranking. Examples are the Transnational Climate Impacts Index (TCI) which accounts for the trade openness of a country (Benzie, Hedlund & Carlsen, 2016) or the Notre Dame Global Adaptation Index (NDGAIN). Supply chain risk assessments (iii) can be built on multi-regional Input-Output (MRIO) or network analyses. For example Wenz & Levermann (2016) provide an assessment of heat-stress related losses in a MRIO model to represent the global supply network combined with a numerical model to introduce more flexibility. Also by the means of MRIO models, the logic of transferring impacts through trade relations has been used to show for example how biodiversity threats or water embodied in goods are imported and exported (Lenzen et al., 2012). With a few exceptions, macroeconomic assessments (iv) with a focus on the industrial sector and

international supply chains are still rare. The ImpactChain project⁷ is analyzing the impact of several slow-onset events on Germany's foreign trade and its implication for the German economy. A similar project is also ongoing for Austria (COIN-INT)⁸.

There is also an analytical modelling base for disasters and the insurance sector. At the aggregate level, a number of insurance and economic catastrophe models have been used to assess and stress-test the impact of high-level climate-related events on national and pan-European insurance and funds. The CATSIM model can conduct stress-testing for high-level climate-related events of risk pools, such as the EU solidarity fund. The Dynamic Integrated Flood Insurance Model (DIFI) (VU) simulates the impacts of climate change scenarios on stylized versions of existing European insurance arrangements (solidarity-based, voluntary-private, public-private partnership, etc.) in the context of flood risk.

Climate cost estimates

In general, the literature on gradual climate change and its impact on industrial products is scarce. Several studies and reports claim that more research is needed on this topic. A few models and projects assess impacts on labor productivity due to heat and humidity. Earlier work focused on the impacts on outdoor work, as work rates decline with rising heat and humidity. Kovats et al. (2011) estimated Southern Europe would incur a mean loss of productivity (days lost) – of 0.4% to 0.9% by the 2080s, with total productivity losses for the EU of EUR 300 – 740 million (A1B). Recent updates (Lloyd et al., 2016) extend productivity losses to three sectors: agriculture, industry, and service, taking account of different work intensities. By the 2050s, they estimate a 0.4% increase in labour time lost for southern Europe, and a 0.2% increase for central Europe South. Productivity losses have also been estimated in CGE analysis at the European and global level (Ciscar et al., 2014; Dellink et al., 2017) and in more depth at the national level (Steininger et al., 2016, in Austria).

There have been some studies of supply chain and procurement risks, focusing on disruptions and delays in delivery and transport due to extremes (Lühr et al., 2014). Lühr et al. (2014) refer to two studies which analyse disruptions of production in general: Allianz Global Corporate & Specialty (2012) estimates that 70% of damages by extreme weather events are linked to supply chain and procurement risks, such as disruptions and delays in delivery; and only 30 % of damages are dedicated to direct physical damages of the production sites. A study by PriceWaterhouseCoopers (2008) determined that 60% of companies affected by production disruptions show a reduction in turnover and rate of return in the following year. In average return on assets decline by 5% and return on sales by 4%. There has also been analysis of supply chain risks using input output models (Wenz & Levermann, 2016) and the risks of climate change on embodied water in imports (Hunt et al., 2014).

According to the literature, the indirect impacts of climate change transmitted by international trade are likely be as important for the European industrial sector as the direct climate impacts on production process (EEA, 2017). Recent reports on the UK, for example, conclude that climate change impacts transmitted by international trade might represent a similar or even greater threat for some parts of the UK economy than domestic climate change impacts (UK Foresight, 2011; PricewaterhouseCoopers, 2013; West et al., 2015). The

⁷ [http://doku.uba.de/aDISWeb/app?service=direct/0/Home/\\$DirectLink&sp=Swww-gates.uba.de%3A4111&sp=SVH01064047%20](http://doku.uba.de/aDISWeb/app?service=direct/0/Home/$DirectLink&sp=Swww-gates.uba.de%3A4111&sp=SVH01064047%20)

⁸ <http://coin-int.ccca.ac.at/>

ImpactChain project for Germany finds that imports from non-EU regions decline by up to 2.1% by 2050 and exports to non-EU regions decline by up to 0.3%. Parts of these reductions are compensated by increased imports from and exports to EU regions, but this partial substitution is insufficient to avert a decline in German GDP and welfare (up to 0.4%).

West et al. (2015) estimated yield changes for four studied commodities (maize, soy, wheat, rice) that show a special relevance for the UK economy. Across all four commodities, the models estimated potential long-term decreases in commodity availability in the countries involved in the UK supply chain of 20-30% under RCP8.5, and up to ~10% decrease for some commodities under RCP2.6.

Case studies on the impact of extreme events on specific regions and/or specific sectors have been undertaken. Haraguch & Lall (2015) analysed the losses in the manufacturing and automobile industry due to flooding in Thailand in 2011. UNISDR (2012) estimated that the flood reduced the world's production by 2.5%. The World Bank (2012) calculated the GDP growth rate with 2.9% significantly lower than the expected rate for 2011 of 4.1%. Within this focus on certain events, some numbers on direct and indirect costs for the considered industry are reported, however, they lack macroeconomic assessments

There are several studies that have looked at insurance. As an example, the ENHANCE project looked at the financial stress from increasing flood risk in the EU (Jongman et al., 2014), finding that with climate change, the EU Solidarity Fund has a substantial and increasing probability of depletion (insufficient funds) (Le Den et al., 2017).

Policies and challenges

While the recognition of mitigation as both a risk and an opportunity has advanced in the business community during the last years, climate change impacts and adaptation has attracted comparatively less attention. Recently, however, business initiatives, such as the Carbon Disclosure Project (CDP) (BSR, 2015; 2016) and the Task Force on Climate-related Financial Disclosure (TSFR, 2017), have started to integrate adaptation into their sustainability and financial reporting.

The major challenge in responding to climate change impacts on international trade lies within the spatial disintegration of the occurrence of the impact and the indirect consequences. The decision-maker's country is often not the one to experience the direct impact (Benzie et al., 2017). Therefore, the global context adds a new dimension to the adaptation-decision space. Up to now, adaptation to internationally transmitted impacts is barely considered in adaptation strategies and plans.

In addition, public adaptation to climate change has manifold impacts on public budgets both on the expenditure and revenue side, however, the quantification of climate change induced effects on public finance is still underdeveloped (Lis & Nickel, 2010). This holds particularly true for impacts transmitted by international trade, and the need to assist climate sensitive countries in their adaptation efforts. The very complex situation for policy makers requires to disentangle the different direct and indirect effects of climate change impacts and adaptation on public budgets, on both the revenue and the expenditure side.

Policy is challenged to address critical intermediate goods for production, such as metallic raw materials. The availability and quality of intermediate goods for production, such as metallic raw materials in production can be affected by climate change. However, macroeconomic modelling and other top-down approaches fail to account for this level of

detail. Hence, a more distinguished approach is needed to analyze the dependency of countries or regions on specific imports from climate-sensitive countries that cannot or only to a very small extent be substituted with imports from other world regions. The industry sector in Europe is threatened more by external risks, especially procurement risks, while internal risks comprise process and management risks. Consequently, industries are required to be informed about their supply chain risks and adapt if necessary. Along these lines, challenges can arise in dealing with an increase in the cost of raw materials, water and energy. This has been acknowledged by some European governments with including this topic in its National Adaptation Strategies. The German Adaptation Strategy, for example, explicitly anticipates new perquisites to make greater efforts than in the past to avoid such dependence for companies that require renewable primary resources (German Federal Government, 2008).

The key policy challenge for the **insurance sector** is to provide broad insurance against increasing climate-related losses that is affordable, efficient, and that promotes risk reduction by policyholders. The trade-off between premium affordability and risk-reduction incentives is an important, yet difficult, challenge for insurance providers to balance, and is often influenced by different risk management and political objectives (Botzen et al., 2009; Penning-Rowsell & Pardoe, 2012; Mechler et al., 2014; Surminski et al., 2015). The EU Adaptation Strategy from 2013 includes an action to promote insurance and other financial products for resilient investment and business decisions. The accompanying Green Paper on insurance has the objective to improve the market penetration of natural disaster insurance and to unleash the full potential of the various policy tools that accompany insurance arrangements. The EU Adaptation Strategy is currently being evaluated and this will most likely result in new or updated recommendations. Furthermore, it is not well understood how climate-related risks (insured and uninsured) cascade through the financial system, i.e. how the impacts on the insurance sector, which also acts as an institutional investor, impacts the financial system overall (Carney, 2015).

Key gaps

This remains an area of low coverage and there are numerous research priorities. There is further work needed to investigate supply chain effects, both in Europe and internationally. The analysis of trade implications on business – extending to macro-economic analysis and the effects on public budgets – is also of interest. The analysis of shocks and tipping points on businesses is also an important research gap. For insurance, the further analysis of climate change on EU insurance arrangements is considered a priority.

Table 15: Summary of key gaps: Business, industry, and trade including insurance

Summary: Business, industry and trade including insurance		
Impact / topic	Quantity and quality of information	Key gaps
<i>Impacts on business, industry and trade</i>		
<i>Supply chain and procurement risks</i>	<i>Moderate</i>	<i>Assessments of disruption of supply chains</i>
		<i>Change in availability/quality of raw materials/critical inputs</i>
		<i>Volatility in prices</i>
<i>Impacts on production processes and management</i>	<i>Moderate</i>	<i>Quantitative implications of labor productivity changes</i>
		<i>Assessment of additional need of cooling and cooling water</i>
<i>Changes in export</i>	<i>Poor</i>	<i>Implications of change in global purchasing power for exports of</i>

<i>markets</i>		<i>European industry sector</i>
<i>Impacts on industry via international trade</i>	<i>Poor</i>	<i>Qualitative assessments with respect to tipping points</i>
		<i>Supply chain risk assessments of extreme events</i>
		<i>Macroeconomic assessments</i>
<i>Trade assumptions in macroeconomic modelling</i>	<i>Poor</i>	<i>Alternative possibilities (other than Armington assumption) to model foreign trade in macroeconomic models</i>
<i>Impacts on insurance sector</i>		
<i>Tipping points in the insurance sector</i>	<i>Poor</i>	<i>Tipping points in the insurance sector have been analysed in a very limited manner.</i>
<i>Role of climate change in insured loss trends</i>	<i>Poor</i>	<i>Anthropogenic climate change has not been detected in insured losses</i>
<i>Policy challenges on business, industry and trade</i>		
<i>Spatial disintegration of impact and consequences</i>	<i>Poor</i>	<i>Necessary to assess various impact chains: trade, migration, biophysical and financial pathways</i>
<i>Analysis of trade implications</i>	<i>Poor</i>	<i>Lack of integrating of trade implications in adaptation strategies and of effects on public budgets</i>
<i>Analysis of criticality of imported intermediates</i>	<i>Poor</i>	<i>Lack of analysis on impacts of changed availability and quality of intermediate goods for production</i>
<i>Policy challenges on insurance sector</i>		
<i>Adapting policies and risk governance systems</i>	<i>Poor</i>	<i>Scope and need for adapting policies and risk governance systems for insurance</i>
<i>Climate-related risks cascading through the financial system</i>	<i>Poor</i>	<i>How do increasing insured and uninsured losses affect the financial system (incl. banks) overall</i>

5. Macroeconomic, growth and competitiveness

Introduction

Most of the studies in the chapters above are sector impact assessments, though some examples of partial and general equilibrium analyses (e.g. in agriculture and energy) have been introduced. However, a number of studies consider the wider economic costs of climate change in Europe and globally. These can investigate the relationship between climate change and economic performance of countries, most commonly represented by indicators of competitiveness, GDP, and, in broader terms, growth. This is a step beyond the computation and then aggregation of costs at the sectoral level as it aims to (a) identify the systemic interactions across different impacts, the economic reaction triggered and transmission channels, this is also called market-driven adaptation (b) assess the effect of these interactions on the overall capacity of economies to produce goods, services and ultimately “welfare”.

Methods for economic assessment

Attempts to quantify the impact of climate change on growth and competitiveness have been made within the last decades, typically using (1) economy-wide simulation models such as computable general equilibrium (CGE) models, (2) integrated assessment models (IAMs), (3) mixed approaches or econometric analyses, and (4) some decision-making tools that explore different probabilities in future states of the world as a response to different levels of uncertainty in models (Fankhauser, 2017).

CGE models usually follow the general equilibrium structure developed by Arrow & Debreu (1954). They depict the economy as a sealed system of monetary flows between producing and consuming agents. These monetary flows base on regional, national, multi-regional or global input-output tables as well as on additional accounting data. Accordingly, CGE models solve numerical equations to find a combination of supply and demand quantities as well as (relative) prices in order to comply with Walras’ Law and simultaneously clear all of the specified factor and commodity markets. Mathematically, CGE models solve optimization problems in which producers minimize their production costs (or maximize profits) subject to technological constraints and consumers maximize their “welfare” (or consumption levels) given budget and resource constraints (factor endowments and consumption functions). Nevertheless, the use of CGE models has simulation character since usually, different counterfactuals that are used in economic impact assessments lead to different solutions of the optimization routine of the model, which then are interpreted as results of different simulation scenarios (Schinko et al., 2017).

The main advantage of CGE models is their ability to capture interlinkages across all agents and economic sectors. In other words, CGE models are capable of quantifying so-called “knock-on” effects of e.g. the introduction of an energy tax, giving a broader picture than isolated sectoral analyses do. As CGE models capture the effects to the whole economy, they enable the analysis of typical macroeconomic indicators such as national production and consumption, welfare, or GDP (cf. Schinko et al., 2017).

Particularly important for the study of competitiveness is the CGE explicit representation of domestic and international trade patterns. These last are typically described according to the Armington approach (Armington, 1969), assuming non-perfect substitution between

domestic and foreign commodities. This eventually allows for characterization of impacts of given policies on both sectoral and country competitiveness measured by market shares and terms of trade effects. This is not usually possible with fully integrated assessment models that are typically one-sector models. Accordingly, on the one hand endogenous price adjustments are not considered, on the other hand international trade is extremely simplified if not absent. That is eventually why competitiveness concerns of climate change policies are mostly addressed with CGE models.

However, there are also disadvantages and challenges to CGE modeling. In order to adequately assess impacts of climate change, a detailed description of the economy, including a representation of climate change related factors that primarily affect markets (such as labor productivity, the energy mix, crop yields or health expenditures), is necessary. Moreover, CGE models may be considered short sighted because they usually assume perfect information and rational behavior solely based on prices, which is unrealistic and thus may lead to somewhat unrealistic results. Moreover, CGE models are often criticized as being insufficiently validated. The performance of the model is often not checked against historical outcomes and key parameters are rarely econometrically estimated (cf. Beckman et al., 2011).

IAMs of global climate change focus on the interactions between the biophysical and the economic system. They aim to assess how environmental pressure is created by economic activity and, in turn, how environmental feedback affects economic growth. The main advantage of IAMs is that they provide an integrated system perspective by coupling different non-holistic models (e.g. a climate model, an energy model, an economic growth model and a land use model). Thereby, IAMs “strip down the laws of nature and human behavior to their essentials to depict how increased greenhouse gases in the atmosphere affect temperature, and how temperature change causes quantifiable economic losses” (Markandya & Halsnaes, 2001). Depending on their specific structuring, some IAMs contain enough detail on the drivers of energy use and energy-economy interaction to calculate the economic costs of different greenhouse gas constraints (e.g. Shogren & Toman, 2000).

According to Markandya & Halsnaes (2001), IAMs can be categorized into a) policy optimization (e.g. cost–benefit models and uncertainty-based models) and b) policy evaluation models (deterministic projection models and stochastic projection models). Even though IAMs have great potential, in the past they often failed to provide an adequate description of the economy or lacked feedback from the biophysical system to the economy (cf. Pindyck, 2015; Stern, 2013; Dellink et al., 2017; Roson, 2003; Rosen, 2016). For this reason, more complex modeling approaches have recently been developed where CGE models are embedded in broader soft linked IAMs - (so called process-based) models - to provide a detailed description of the economy and to take into account the highest possible detail on the feedback from climate impacts on the economic system.

Next to the two modelling approaches described above, econometric literature provides additional evidence on the correlation between a climate stressors (e.g. temperature, precipitation) and economic growth. This strand of literature usually tries to extrapolate future trends by analyzing historical relationships of climate variables and economic activity. Studies using micro-level data aim to identify how certain components of economic production, such as labor productivity or crop yields, respond to different (and changing) temperature levels (see Schlenker & Roberts, 2009 or Graff, Zivin & Neidell, 2014). Studies using macro-level data analyse correlations between temperature and precipitation and

total economic output over time (see Dell et al., 2012 or Hsiang, 2010) and across space (see Nordhaus, 2006 or Dell et al., 2009). Current developments in econometric models include considerations for nonlinear effects, spatial and temporal displacement and delay, statistical uncertainty, inclusion of adaptation, and allows for the comparison of results across studies (Hsiang, 2016). In general macroeconometric assessments detect a lower impact of climate change on economic activity than microeconomic assessments (Burke et al., 2015).

Research with focus on climate change, growth and competitiveness can be very diverse regarding a) geographic and sectoral coverage and b) complexity and richness in detail. While some macroeconomic models focus more on the broad picture, others aim to describe single countries or even single sectors within one country in more detail.

Climate cost estimates

The OECD used the ENV-Linkages model (OECD, 2015) to estimate the economic costs of climate change through to 2060. The central projection of the CGE model, which presents the “best guess” estimate of damages, leads to global GDP losses that gradually increase to a total of 1.5% in 2060. For OECD Europe⁹, agriculture and trade exposed industries benefit from improved international trade, while the service sector is hurt by domestic tourism and health impacts, as well as from reduced capital availability due to sea level rise. Dellink et al. (2017) again use the ENV-Linkages model in combination with the AD-DICE model. They use a novel production function approach to identify the aspects of economic growth directly affected by climate change. Results on global level show that projected damages raise twice as fast as global economic activity, and that GDP losses are projected to be 1.0–3.3% by 2060 (Dellink et al., 2017).

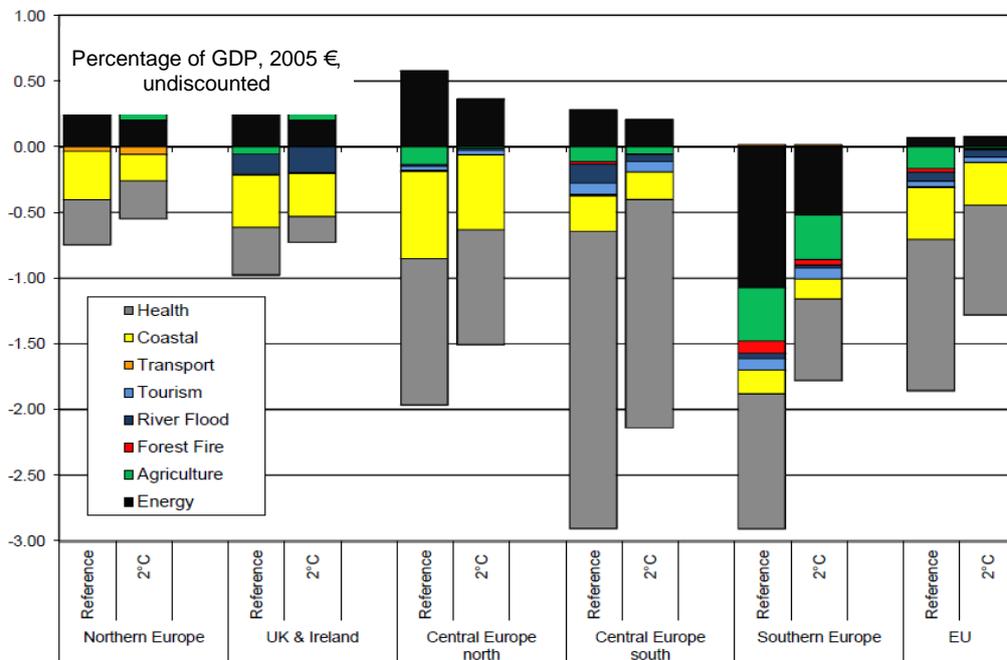
Eboli et al. (2010) were able to account for the interaction between exogenous (and climate-change-induced) shocks on the economic system and endogenous capital and foreign accumulation processes, using the ICES model. They find significant distributional effects at the regional and industrial level in favor of the industrialized world, leading to higher inequality in wealth distribution. These results are consistent with other sources, such as Dell et al. (2008) and Bosello et al. (2012). Bosello et al. (2012) also discovers a slightly positive effect of climate change on EU GDP in 2050 (+0.01%). Northern European countries benefit (+0.18%), while Eastern European (-0.21%) and Mediterranean (-0.15%) countries lose GDP due to climate change. While agriculture impacts strongly affect low latitude and less developed regions, the redirection of tourism flows due to climate change highly affects different EU regions. Generally, tourism flows will be gradually re-directed from warmer to colder regions, leading to gains in Northern Europe on the detriment of Mediterranean and Eastern Europe.

The PESETA II study used a CGE model to look at the economic effects from direct climate effects and the indirect effects in the economy (Ciscar et al., 2014). Under the reference scenario (SRES A1B) (featuring a median temperature increase of roughly 3°C by the end of the century), they estimated the annual total damages from climate change in the EU would be around EUR 190 billion (with a net welfare loss estimated to be equivalent to 1.8% of current GDP, see Figure 4) by the end of century, with particularly high costs in southern European regions. These impacts would be reduced to EUR 120 billion (equivalent to 1.2% of current GDP) in a 2°C world. While a significant proportion of the damages are due to

⁹ including the EU plus Iceland, Norway, Switzerland, Turkey and Israel

heat-related mortality (noting cold-related benefits were excluded, and values are driven by the valuation approach used), coastal damages and the agriculture sector are also quite significant. However, the assessment only covered a limited number of sectors (and impacts within these), and these can only be considered partial, especially due to the omission of potential impacts on biodiversity and ecosystem services.

Figure 4: Welfare impacts of climate change for EU regions, 2071–2100. Source: Ciscar et al. (2014)



There have also been a number of regional assessments. For example the CIRCE project (Navarra & Tubiana, 2013) estimated the economic costs of impacts in the Mediterranean region. Estimates, using a computable general equilibrium model under SRES A1B emissions, suggest negative economic consequences being projected for major sectors, such as tourism and energy. Furthermore, all Mediterranean countries could lose an averaged 1.2% of GDP in 2050. The largest economic costs relate to sea-level rise and tourism.

Research on national level is capable of providing more detailed information on single (economic and non-economic) sectors and thereby highlight geographical and sectoral differences. Studies on national level have been provided e.g. for Austria (Steininger et al., 2016), Greece (BoG, 2011), Italy (Sgobbi & Carraro, 2008) and Sweden (Swedish Commission on climate change and vulnerability, 2007).

Steininger et al. (2016) find that current welfare damage of climate and weather induced extreme events in Austria is estimated at an annual average of about EUR 1 billion (large events only, mainly relate to river flooding). These damages may potentially rise to EUR 4-5 billion by mid-century (annual average, known impact chains only, undiscounted), with an uncertainty range of EUR 4-9 billion. Even for a partial analysis of extreme events, damages may rise significantly by the end of the century, e.g. with an estimated increase to EUR 40 billion.

For Italy, aggregate GDP losses induced by climate change are likely to be small, according to Sgobbi & Carraro (2008). It finds, however, large sectoral differences and estimates that climate change will have a significant negative impact on the tourism sector in Italian alpine regions.

Estimations by the Bank of Greece (2011) highlight significant negative effects of climate change on the overall Greek economy. It finds that the impacts of climate change are negative for all relevant sectors in Greece. Three scenarios carried out within economic impact assessments estimate that because of climate change, Greece's GDP drops by around 2% in 2050 and by 3-6% in 2100. Largest damages are accounted to the tourism sector, which is a crucial source of revenue for the Greek economy.

The Swedish Commission on climate change and vulnerability (2007) finds highly diverse effects of climate change on different sectors of the Swedish economy. On the one hand, it found large positive effects of climate change on hydropower production. By the end of the century, calculations indicate a possible increase in hydropower potential averaging 15-20%. On the other hand, coastal erosion, flooding and landslides will cause significant damages. As temperatures will rise during the next decades, the Swedish winter tourism industry will be negatively affected, while summer tourism could benefit.

It is stressed that the GDP estimates above are partial. Even within the sectors covered, the analysis considers a sub-set of the possible effects of climate change, both positive as well as negative. There are important sectors for which estimates are not reported above (e.g. business and ecosystems). There is also little quantitative evidence on how impacts internationally will impact within Europe. Finally, these estimates involve high uncertainty, which is not captured by central projections, but are critical in considering adaptation.

Triple E Consulting (2014) quantified the **impacts of climate change on employment** within different EU sectors. According to the estimates of the baseline scenario, approximately 410,000 jobs will be lost by 2050 due to climate change if no further adaptation is taking place. In the short-run, up to 2020, 240,000 jobs would be lost. Distributional effects suggest positive effects in Scandinavia and other parts of Western Europe (Great Britain, the Netherlands, Ireland and Belgium), but even more negative effects in Bulgaria, Slovenia, Estonia, Slovakia, Czech Republic and Croatia (Triple E Consulting, 2014).

There is relatively little literature on **competitiveness**. De Voldere et al. (2009) aim to a) assess the competitiveness of the EU tourism industry and b) identify existing barriers hampering the competitiveness of the sector in Europe. By means of a SWOT analysis, the study identifies the main challenges to enhance the competitive position of the EU tourism industry and suggests actions to overcome the challenges.

A further issue is the potential impact of climate change on the **drivers of growth** (i.e. economic growth rates) and not just levels of outputs. For instance, the econometric literature (Dell et al., 2012 and Burke et al., 2015), which captures non-linearity in environmental and economic responses, suggests that climate does have negative effects on growth (at least in less developed countries). Economic costs are roughly 10-fold greater than the CGE studies mentioned above. When this issue has been assessed with GCEs (notably OECD, 2015), effects have been detected, but they are (relatively) modest.

Results from Dell et al. (2012) suggest that depending on the specification, higher temperatures may not simply reduce the level of output, but the growth rate of poor countries. The study estimates that for poor countries, higher temperatures have large, negative effects on growth. In particular, a temperature rise of 1°C in a given year is estimated to economic growth (in the same year) by about 1.3 percentage points. In rich countries, however, effects of temperature were not found to have robust, discernable effects on growth. It finds evidence that temperature affects poor countries' economies in

various dimensions and in ways that are consistent with potential growth effects. Not only agricultural output concentrations, but also adverse effects of hot years on industrial output are expected. In addition, results suggest that higher temperatures lead to political instability in poor countries, which could possibly reduce the growth rates of a country.

Burke et al. (2015) tried to unify the results from analyses on micro- and macro-level by accounting for non-linearity at the macro-scale. Their results show that the relation between economic productivity and temperature is non-linear for all countries, and that productivity levels peak at an annual average temperature of 13°C. Results suggest that if future adaptation mimics past adaptation, climate change could reduce global output by 23% in 2100 and widen global income inequality. In this scenario, average income in the poorest 40% of countries declines by 75%, while the richest 20% of countries experience slight gains, compared to a world without climate change. These large numbers, however, stem from taking extreme events and projecting as slow onset change. Therefore, results from Burke et al. are highly debatable and do not coincide with projections from inter alia OECD (2015).

Key gaps

There is a need to develop consistent and harmonised European economic cost estimates, including disaggregated estimates at national and subnational levels. This requires improving the interlinkages between process-based and sector analysis and the CGE models. Additional priorities include analysis on the impacts of climate change on growth rates (drivers of growth) and analysis of sectoral differences and changes in the level of competitiveness. Further research priorities include the integration of trade and market effects, as well as representation of major extremes and tipping points.

Table 16: Summary of key gaps: Macroeconomic, growth and competitiveness

Summary: Macroeconomic, growth and competitiveness		
Topic	Quantity and quality of information	Key gaps
<i>The impact of climate change on the drivers of growth</i>	<i>Poor</i>	<i>Unclear how and how much climate change impacts the drivers of growth, especially its “non linear effects” (one of the potential explanation of the “divide” between econometric and model based assessments)</i>
<i>Incorporating the dynamic nature of climate change</i>	<i>Poor to moderate</i>	<i>Climate change is often analysed in a comparative static environment and tipping points are poorly represented</i>
<i>The impact of climate change on multi-regional national, regional GDP growth</i>	<i>Very good</i>	<i>No significant gaps - on national or macro regional scale. Significant gaps on the sub-national assessments of climate change costs.</i>
<i>The impact of climate change on multi-regional, national, regional competitiveness</i>	<i>Moderate</i>	<i>Climate-change driven competitiveness effects at the national level are rarely considered</i>
<i>The impact of climate change on sectoral growth and competitiveness</i>	<i>Poor to moderate</i>	<i>Gaps remain in all EU countries except Austria (and maybe the Mediterranean area)</i>

6. Tipping points

The term “tipping point” has become a popular term in the climate change domain, among the scientific community as well as in public debate (Russill & Nyssa, 2009). Within the scientific discourse on climate change and its impacts, the use of the term ranges from very strict definitions in the dynamic systems literature – where tipping points are mathematically defined as bifurcations or critical transitions (e.g. Scheffer et al., 2009) - to more loose definitions where the concept is metaphorically applied to indicate that small causes may have large effects.

There are four main focus areas in the literature on tipping points. The first three define critical thresholds at which a system abruptly shifts from one state to another due to a small change in conditions (Scheffer et al., 2009). These shifts can take place in (1) the climate (2) ecological or (3) socioeconomic systems (Box 1). The fourth area is policy tipping points, representing fundamental changes in actions or policies in response to climate change.

Box 1 Strict definitions of Tipping Points

Strictly defined, tipping points are “reached when the system in question surpasses a critical threshold at which a rather small additional perturbation can cause a comparatively abrupt and significant shift in the system configuration, moving it from one state to another” (Garschagen & Solecki, 2017, p.1, cf. Scheffer & Carpenter, 2003) Other strict definitions require properties like: (Kopp et al., 2016).

- Results from a strong positive feedback inside the system, i.e. “a closed loop of causal connections that are self-amplifying, tending to magnify any perturbation” (Lenton, 2013, p.2)
- The effect (change in system state) is relatively large compared with the cause (changing conditions) of the shift
- Concerns a shift (transition) from one stable state to another
- The shift should occur quickly (abrupt)
- The behaviour of the shift should be non-linear
- The system change is initiated by an external forcing, but does no longer need this to sustain the pattern of change, i.e. “the moment at which internal dynamics start to propel a change previously driven by external forces” (Walker, 2006, p.802)
- (Ir)reversibility is often seen as an important property of tipping points, indicating whether or not one can simply turn back to the original state by reverting the system conditions back to its original state (Lenton, 2013). The term *hysteresis* is used when the path back to the original state significantly differs from the original path (Scheffer & Carpenter, 2003).

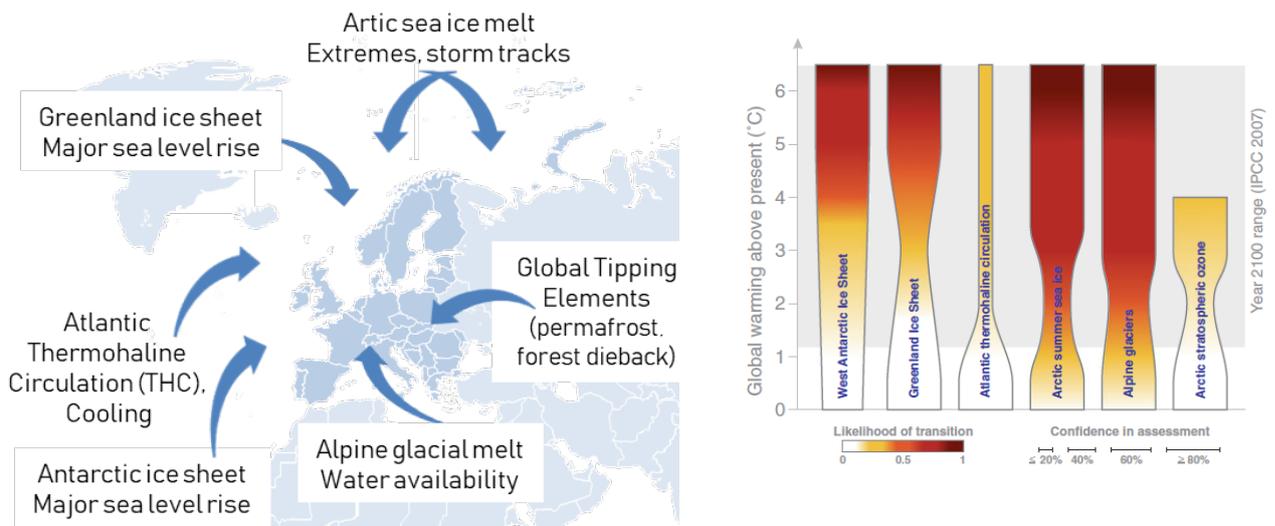
Two further dimensions of tipping points are also important to highlight. Firstly, their (ir)reversibility i.e. whether or not one can simply turn back to the original state by reverting the system conditions back to their original state (Lenton, 2013). Secondly, and especially for socioeconomic tipping points, is the issue of scale. At a local level, climate change may have large socioeconomic impacts (e.g. closure of a low-lying ski resort), whereas at a European scale, the knock-on effect of such an impact may be limited.

6.1 Biophysical tipping points

Climate tipping points are one of the key motivators for ambitious global climate mitigation policy, yet they are poorly represented in most assessments of the economics of climate change. They relate to tipping elements at sub-continental to global scale that could, as a

results of climate change, lead to a qualitatively different state with large-scale consequences. Lenton et al. (2008) compiled a list of possible global tipping elements and Levermann et al. (2011), looked at the most important tipping elements for Europe (see Figure 5) and make indicative estimates of the level of climate change that might trigger them.

Figure 5: Map of potential policy relevant tipping elements of the climate system in Europe and estimates of level of global warming that might trigger a transition. Sources: Levermann et al. (2011); Lenton et al. (2008).



Two tipping points of concern are likely in the short term:

1) The disappearance of Arctic summer ice (projected under global warming of 1–2°C) is associated with cold Eurasian winters, increased probability of extreme cold events, changes of Atlantic storm tracks into Europe and impacts on Arctic ecosystems. There may also be some potential benefits in terms of navigation times and access to Arctic resources. There has been some economic analysis of the impacts of this tipping point on global costs of climate change in the EU ICE-ARC, but has not considered the direct economic costs in Europe.

2) Models project that at 2°C of global warming (+3–4°C locally) there could be an almost complete loss of glacier ice volume in the Alps. This will affect water availability in the region, especially as glaciers shrink (with increased short-term flows from melt water) affecting hydropower and stability/ landslides.

Beyond this, the major risks arise from rapid sea level rise (SLR), either from the accelerated melt of the Greenland Ice Sheet (leading to global SLR of 7m) and/or the accelerated melt or possible collapse of the West Antarctic Ice Sheet (leading to SLR of 5 m). Although it would take centuries for such rises to occur, positive feedbacks can increase surface temperature and melt rate which may cause rapid shrinkage in the ice sheet upon passing a certain tipping point (Lenton et al., 2008) causing rapid global SLR.

Finally, climate change beyond a certain threshold may trigger a collapse of the Atlantic Thermohaline Circulation (THC) resulting in a large decrease of temperature in Northwest Europe with large socioeconomic consequences (Rahmstorf & Ganopolski, 1999; Lenton et

al., 2008). Latest studies use stochastic Integrated Assessment Models (Lontzek et al., 2015, Cai et al., 2016) and some also analyse tipping point interactions (Lemoine & Traeger, 2016).

Ecological tipping points denote ‘regime shifts’ or ‘critical transitions’ in smaller scale biophysical systems (Scheffer & Carpenter, 2003). Some of these can be induced by climate change as well, such as glacier melts, desertification and forest diebacks. For example, increase in lake temperatures may lead to rapid and abrupt reduction of fish habitats (Smol et al., 2005 as cited by Liu et al., 2015) and gradual sea level rise may reduce coastal habitats to such extents that certain species will no longer survive (Schröder Esselbach, 2018).

The evidence base on economic estimates for tipping points is very limited. Brown et al. (2012) estimated the economic costs of 1.4 metres of sea level rise in the EU at EUR 156 billion/year by the 2080s – six times higher than the A1B scenario. The recent RISES-AM study estimated that with 2.5 metres of sea level rise, the 21st century cumulative economic costs in Europe could rise to EUR 18.8 trillion (without additional adaptation), approximately equivalent to today's EU GDP. Lontzek et al. (2015) estimated damages of 10-20 % of world GDP for a collapse of the THC and there are some studies using stochastic Integrated Assessment Models (Lontzek et al., 2015; Cai et al., 2016).

The HELIX project on high-end scenarios has been looking at tipping points but has not published results yet.

6.2 Socio-economic tipping points

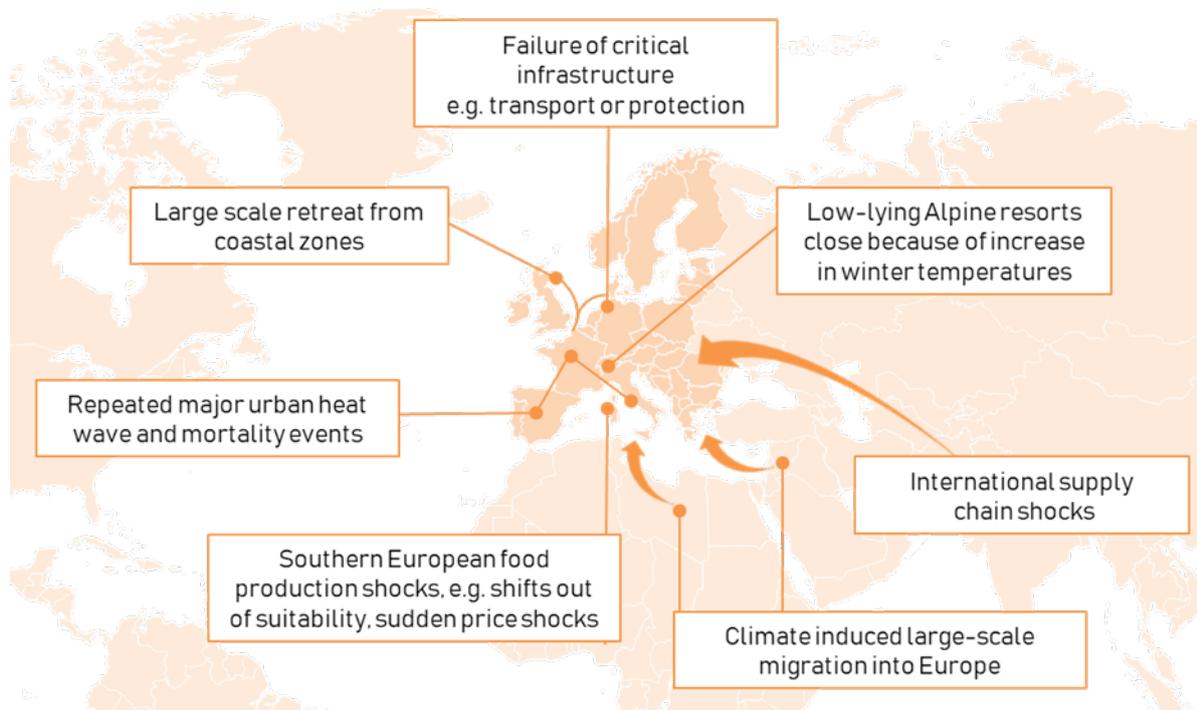
Within COACCH we have initially defined a socioeconomic tipping point as: “a climate change induced, abrupt change of an established socio-economic system’s functioning into a new functioning of fundamentally different quality (beyond a certain threshold that stakeholders perceive as critical).”

It is more difficult to translate the strict definition of tipping points into the socio-economic domain, and there are different types of pathways that may occur. These may involve a case where climate change triggers a large-scale socio-economic event (a major shock). It might also involve climate change (above a threshold) affecting the functioning of an established socio-economic system. Either of these might involve feedback loops (and amplification), and they could be non-linear and irreversible. They could therefore trigger a rapid increase in costs, e.g. as measured by a large drop in the GDP of a region, or they may require a fundamental new functioning of an existing system with high associated costs.

Especially for socioeconomic tipping points, the *issue of scale* seems important. At a local level, climate change may have large socioeconomic impacts, whereas on a European scale, the impact is limited. For example, a small increase in temperature may cause a low-lying ski resort to close, but does not have major impact on overall winter sport revenues in the Alps. Similar for agriculture: temperature increase may make a specific region unsuitable for production of certain types of wine, whereas on a European scale, we observe a shift in wine production regions rather than an overall tipping point for the wine sector (examples from IPCC, 2014). Other examples include where climate change causes a long period of drought triggering a violent conflict in the Middle East (Caruso, 2017), which could be a trigger for migration (cf. McLeman et al., 2017 for an extensive discussion on migration in the context of adaptation to climate change).

The concept of socio-economic tipping points has not yet been used explicitly in the literature. However, several examples exist where climate change may cause abrupt shifts in socio-economic circumstances.

Figure 6: Illustrative socio-economic tipping points



Below we make an inventory of these candidate socio-economic tipping points, which will be further explored within the COACCH stakeholder co-design workshop (see [D1.3 workshop report](#)). Note that some of the examples provided may not meet all criteria of ‘true tipping points’, depending on the definition used.

Agriculture and forestry

In agriculture, temperature and precipitation changes result in different crop suitability, which tend to be gradual, until a certain threshold is reached (Brown et al., 2017, citing IPCC, 2013). Small crop failures may be balanced by storage (Schewe et al., 2017), but recurring heat waves and droughts may cause shortages that cannot be balanced by the available storage. Irreversible food production shocks may lead to a socio-economic tipping point in Southern Europe: rapid and substantial increase of food prices, food insecurity and riots.¹⁰

According to the IPCC (2014) fire frequency and wildfire extent will increase in Southern Europe (cf. Lozano et al., 2017). Current 100-yr wildfire events will occur every 5-50 years with substantial consequences for local communities and economies (Forzieri et al., 2016).

On a local scale, climate change can have a large impact on agricultural practices. In the wine production for example, higher temperatures change the ratio between sugar and acids, which changes the unique characteristics of wine that are crucial for the industry. (IPCC, 2014)

¹⁰ Example provided by Esther Boere, IIASA. Similar stock-depletion dynamics are observed for groundwater storage: recurring droughts may potentially have dire consequences for economic and food security in the USA (Famiglietti et al., 2011).

Scientists are concerned that climate change may negatively influence the process of pollination, because insect flight dates and crop flowering dates are differently influenced by earlier spring warming (Robbirt et al., 2014). Pollination is an important process for successful agriculture. Some recent work has been published on the occurrence of tipping points in these type of systems (Jiang et al., 2018).

Health

In Europe, extreme temperatures take more lives than any other natural disasters (de' Donato et al., 2015, citing WMO). Merte et al. (2017) estimates that in Europe, around 28,100 people die annually due to heat waves, mainly in Portugal, Spain and France. De' Donato et al. (2015) find a relation between extreme temperatures and elderly mortality rates in several European cities. This relation shows tipping point behaviour for temperatures above 25-30°C.

According to the IPCC (2014a, 2014b), changes in temperature and rainfall may spatially alter the occurrence of vector-borne diseases, which could be a concern for health in Europe.

Migration

Climate induced environmental change is a driver for migration (McLeman et al., 2017) and the resulting migration flows may give rise to conflicts via several pathways (Reuveny, 2007). Therefore, large migration towards Europe can be considered a climate-induced socio-economic tipping point. However, the popular notion of 'climate refugees' has been criticized by several scholars who pointed out that social, political, demographic and economic drivers play a co-determining key role in explaining refugee flows (Freeman, 2017; Bettini, 2017). Nevertheless, we think that changes in several climate variables (e.g. sea level rise, flood and drought events) and their influence on migration flows towards Europe is a field of research worth exploring within COACCH.

Transport infrastructure

The impact of climate change on the transport sector is mainly determined by changes in extreme weather and flood events. On a European scale, climate change seems to have net positive impact on road maintenance costs, because an increase in heat stress costs is outweighed by a decrease in winter maintenance cost. Extreme heat events have large adverse impacts on the rail and inland shipping sector. Extreme weather and natural disasters will typically impact multi modes at the same time. Damage may reinforce when different modes depend on the same critical network infrastructures (e.g. ports) or have strong supply chain dependencies. On the other hand, a change in modal split may have a damping effect on overall costs. (EU WEATHER and EWENT projects)

A potential tipping point on European scale is coastal flooding of a critical infrastructure, such as the Rotterdam harbour, causing an international economic shock (Koks et al., 2016). Actual flood events of this magnitude occurred in Fukushima (2011) and New Orleans (2005). Climate change may cause significant changes in passenger (tourism) and freight (agricultural) transport patterns in Europe. On a national scale, widescale failure of dikes may cause large riverine flooding. Increased pluvial flooding due to increased extreme precipitation events may lead to unacceptable damages to highway networks linking key economic areas. In less developed countries, heavy rainfall may cause large wash-away of rural roads. On a local scale, coastal erosion may threaten parts of the railway and road

infrastructure (Dawson et al., 2015). Extreme precipitation may lead to severe network disruption on the urban scale and significantly hinder emergency response (Rowley et al., 2016).

Warming conditions in the Alpine regions may alter the risk of landslides and avalanches (Huggel et al., 2012) that may have profound consequences on road and rail infrastructure in mountain areas.

Coastal erosion and built environment

In several parts of Europe, coastal erosion is a problem for the built environment. On a European scale, large-scale retreat from coastal zones as a result of large sea level rise can be considered a socio-economic tipping point. More likely however are the local examples: threatening of coastal resorts in the UK (Haugh, 2014); collapse of Soviet-era coastal defense in Ukraine leaving the coast unfit for tourism (Pranzini et al., 2015); widespread erosion along the Alexandroupolis coastline in North-Eastern Greece threatening ancient heritage (Xeidakis et al., 2007); and erosion around a nuclear waste depository in Estonia (Fay et al., 2010).

Policy tipping points

The introduced notion of *socio-economic tipping points* has overlap with two existing branches of literature: *adaptation tipping points* (Haasnoot et al., 2013) and *transformation tipping points* (Moser & Dilling, 2007), which can be summarized as *policy tipping points*. Adaptation tipping points are reached when external change leads to unacceptable performance of policies. In literature on social transformations towards a sustainable world, tipping points indicate the point where the transformation is not only adopted by a few early adaptors, but rapidly spreads over the majority of actors.

The potential occurrence of biophysical and socio-economic tipping points will lead to a policy response often well before the actual physical tipping occurs, aiming at avoiding the climate tipping point (mitigation) or reducing the impact on the socio-economic system (adaptation). This could require significant and transformative shifts in EU policies: a policy tipping point.

6.3 Key gaps

The entire field of tipping points is a priority for economic research. Socio-economic tipping points in particular, is an emerging concept that requires definition and consideration of scale. This includes the development of a typology to categorise different types of socio-economic tipping points in order to be able to quantitatively assess them and estimate potential economic costs. Research is needed to understand the potential climate thresholds that could trigger these events, considering their likely occurrence for different scenarios (using CMIP5) over the current century.

Regarding tipping point economic assessment, the available studies analyse some tipping elements mostly focusing on the Atlantic Thermohaline Circulation (see Lenton & Ciscar, 2013 for a review). Latest studies use stochastic Integrated Assessment Models (IAMs) (Lontzek et al., 2015 and Cai et al., 2015), analyzing also tipping point interactions (Lemoine & Traeger, 2016). While these analyses rely on IAMs with a coarse regional and geographical aggregation, there is room for improvements in the economic assessment by extending the

granularity of the analysis, and focusing on several elements at the same time using a general equilibrium framework as suggested by Lenton & Ciscar (2013).

Table 17. Summary of key gaps: Tipping points

Summary: Tipping points		
Topic	Quantity and quality of information	Key gaps
<i>Definition of socio-economic tipping points</i>	<i>Poor</i>	<i>No agreed-upon definition</i>
<i>Examples of socio-economic tipping points</i>	<i>Poor</i>	<i>No comprehensive overview of examples in Europe</i>
<i>Policy tipping points</i>	<i>Poor</i>	<i>Will climate change require large transformations (tipping) of EU policies?</i>

7. Conclusions

The report summarizes the existing knowledge on the economic costs of climate change impacts in Europe and upcoming or ongoing policy challenges in the different sectors. Based on detailed review of EU research projects and scientific articles, key gaps for the different sectors and risks have been identified.

On the economic costs of climate change, the the knowledge base has been analysed for 13 different sectors and risks: agriculture, forestry & fisheries, tourism, health, inland flooding & water management, coastal flooding, energy, transport, biodiversity, and business & insurance. The findings of this review are that the most comprehensive coverage on economic assessments of climate costs is found for coastal zones and inland river flooding. Comprehensive modeling approaches are already available for these sectors. The main gaps for river flooding are the linkages between bottom-up and top-down approaches, the estimation of indirect costs of flooding and the evaluation of multi-flood hazards. For coastal flooding, a further improvement of economic estimation of adaptation measures is mentioned as well as tipping points connected to coastal zones.

The agriculture sector has fairly good coverage, although there are gaps on the effects of extremes, and interlinkages between agriculture and forestry sector including bio-energy sector. There are more gaps for forestry & fisheries, including gaps on the estimation of climate impacts on biophysical elements, forest productivity or shifts in forest species, and particularly impacts of pest and diseases. Furthermore, the comprehensive estimation of impacts, costs and benefits of adaptation activities needs to be improved.

For the energy sector, there is some coverage on energy supply and demand side. However, gaps exist on the impacts on energy security in general, impacts of extreme events on cooling demand and the costs and benefits of adaptation options, as well as the impacts of extreme events on the production of different renewable energy source such as hydropower, wind, and thermal generation.

For the transport sector, studies exist for the costs on inland waterways and the buckling of rail infrastructure according to heat events. Remaining gaps are highlighted for road infrastructure, transport hubs, including ports and indirect cost effects of transport disruptions.

A variety of studies exist for the tourism sector, mainly focusing on winter tourism in the Alps and summer tourism in the Mediterranean area. Major gaps remain for other regions, and for nature tourism. Furthermore, there is little information on the costs and benefits of adaptation measures as they are often local and region specific.

The coverage of climate cost assessments for business, industry, trade and insurance is limited. There have been assessments of the impacts on labour productivity. There have also been some studies of supply chain and procurement risks, focusing on disruptions and delays in delivery and transport due to extremes, but supply chain risk assessment remains a major gap. The indirect impacts of climate change transmitted by international trade could be far more important for the European industrial sector than direct impacts on the affect production sites in Europe, tough quantitative risk assessments and macroeconomic assessments with a focus on the industrial sector and international supply chains are as well still rare.

Biodiversity and ecosystems was identified as areas with a very low coverage on economic assessment of climate change.

The findings are summarised in the following table.

Table 18: Coverage of existing knowledge on Economic Costs of Climate Change in Europe

Risk / Sector	Coverage of Economic Analysis / Policy	Cost estimates
Coastal zones and coastal storms	Comprehensive coverage (flooding and erosion) of economic impacts at European, national and local level. Applied adaptation policy studies including decision making under uncertainty (DMUU).	✓✓✓
Floods including infrastructure	Good coverage at European, national and local level, especially for river floods (less so urban). Applied policy studies including adaptation / DMUU.	✓✓✓
Agriculture	Good coverage of European and national studies (partial and general equilibrium). Studies of farm and trade adaptation. Emerging policy analysis on adaptation and economics.	✓✓
Energy	Studies on costs of energy demand (heating, cooling) and supply (hydro, wind). Many policy studies on mitigation. Low coverage on adaptation.	✓✓
Health	Good coverage of European and national heat related mortality. Some estimates for food-borne disease. Lower coverage for other impacts. Emerging evidence base on adaptation policy (heat).	✓✓
Transport	Some European studies on road and rail infrastructure (extremes). Limited studies for air and indirect effects. Limited adaptation policy analysis.	✓✓
Tourism	European and national studies on beach tourism (Med.) and winter ski tourism (Alps). Low information on nature-based and other tourism. Low level of policy analysis.	✓✓
Forest and fisheries	Limited studies of economic impacts on forestry (productivity). Some studies on European forest fires. No economic studies on pest and diseases. Limited studies of economic impacts on marine or freshwater fisheries.	✓
Water management	Some national and catchment supply-demand studies (and deficit analysis), though lack of European wide cost studies. Limited policy and cross-sectoral adaptation studies.	✓
Business, services and industry	Low evidence base of quantitative studies. Some studies on labour productivity. Limited analysis of economic impacts on supply chains.	✓
Macro-economic analysis	Several pan-European studies using CGE models. Low coverage of effects on drivers of growth, employment, competitiveness.	✓
Biodiversity / ecosystem services	Very low evidence base on economic impacts. Adaptation policy studies limited (only restoration cost studies).	x
Climate tipping points	Some studies of economic costs of major sea level rise in Europe (>1m). Low economic coverage other bio-physical climate tipping points.	✓ / x
Social-economic tipping points	Emerging interest in socio-economic tipping points (migration, food shocks) but no economic analysis	x

Key= ✓✓✓ = High coverage. ✓✓ = Medium coverage. ✓ = Low coverage. x = Evidence gap.

Based on the work on existing knowledge, research gaps were defined and discussed with stakeholders from different groups (business, investment, policy making, research). The discussion results are summarized in the COACCH report [D1.3 Workshop results](#).

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9. Annex 1: Comparison of the main elements of crop models

Table 1: Comparison of the main elements of crop models

Model name	Characteristics	Climate input variables	Extreme weather events that can be modeled	Outputs	Main Reference
Environmental Policy Integrated Climate Model (EPIC)	Dynamic simulation based on development and growth processes using water, temperature, heat, oxygen, nitrogen, phosphorus, bulk density and aluminium stress as inputs.	Minimum temperature, maximum temperature, phosphorus, relative humidity, wind speed.	Water, temperature, heat	plant growth, crop yield, tillage, wind and water erosion, runoff, soil density, and leaching, water and fertilizer requirement Actual yields under management systems, including irrigation	Williams (1995); Izaurrealde et al. (2006)
Global AgroEcological Zone Model in the Integrated Model to Assess the Global Environment (GAEZ-IMAGE)	Dynamic simulation based on development and growth processes using water and temperature stress as inputs	Average temperature, phosphorus	Water, temperature	Potential yield	Leemans and Solomon (1993); Bouwman et al. (2006)
Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model (LPJmL)-	Simulates Transient changes in carbon and water cycles due to land use, the specific phenology and seasonal CO ₂ fluxes of agricultural-dominated areas, and the production of crops and grazing land and water and temperature as inputs	Average temperature, phosphorus, cloud cover	Water, temperature	Treatment of residues, intercropping Biophysically-based model able to project yields on the basis of local agro-climatic conditions Actual yields under management systems, including irrigation	Bondeau et al. (2007); Fader et al. (2010)

Lund-Potsdam-Jena General Ecosystem Simulator with Managed Land (LPJ-GUESS)	Dynamic simulation based on development and growth processes using water, temperature as inputs.	Average temperature, phosphorus, cloud cover	Water, temperature	Potential yield under management systems, including irrigation	Bondeau et al. (2007) Smith, Prentice, and Sykes (2001)
CropSyst	Cropping systems simulation model developed to serve as an analytical tool to study the effect of climate, soils, and management on cropping systems productivity and the environment			soil water and nitrogen budgets, crop growth and development, crop yield, residue production and decomposition, soil erosion by water, and salinity	Stöckle, C.O., Donatelli, M., Nelson (2003)
parallel Decision Support System for Agro-technology Transfer (pDSSAT)	Dynamic simulation based on development and growth processes including water, temperature, heat, oxygen and nitrogen as inputs.	Minimum temperature, maximum temperature, phosphorus, radiation	Water, temperature, heat.	Actual yields under management systems, including irrigation	Jones et al. (2003)
Predicting Ecosystem Goods And Services Using Scenarios (PEGASUS)	Dynamic simulation based on development and growth processes including water, temperature, heat, oxygen, nitrogen, phosphorus and potassium stress as inputs.	Average temperature, minimum temperature, maximum temperature, phosphorus, cloud coverage	Water, temperature, heat	Actual yields under management systems, including irrigation	Deryng et al. (2011)

Table 2: Comparison of CGE and PE models in terms of how climate-induced yield changes can react to cropland expansion and crop productivity

Models	Effect of climate change on crop productivity	Impact of climate on cropland	Main reference / institution
Computational General Equilibrium (CGE)			
Asia-Pacific Integrated Model (AIM)	Crop productivity model that provides potential productivity	Land conversion between primary land, secondary land, cropland, pasture and urban land	(Matsuoka, Morita, and Kainuma 2001) - NIES
ENVironmental Impact and Sustainability Applied General Equilibrium model (ENVISAGE)	Exogenous variables or factor productivity is directly impacted by changes in temperature through damage functions	Land conversion between crops, livestock and forestry	(Mercato 2006) - World Bank / FAO
Emissions Prediction and Policy Analysis Model (EPPA)	Terrestrial ecosystem processes (cycles of C, N and water) provide yields and primary productivity	Land conversion between cropland, pasture, harvested forest, natural grassland and natural forest land	(Paltsev et al. 2005) - MIT
Future Agricultural Resources Model (FARM)	Exogenous change in productivity due to carbon fertilisation	land allocation between cropland, livestock and forestry and between crops within cropland	(Stern 2001) - USDA
Global Trade Analysis Project (GTAP)	Productivity changes taken from exogenous projections	land allocation between cropland, livestock and forestry and between crops within cropland	(McDougall and Golub 2007) - Purdue University
Integrated Model to Assess the Global Environment (IMAGE)	Potential distribution of crop production and potential productivity of crops based on separate models	Computes deforestation and land abandonment. Within productive use differentiation between field crops and pasture	http://themasites.pbl.nl/models/image/index.php/Welcome_to_IMAGE_3.0_Documentation - PBL
Modelling International Relationships in Applied General Equilibrium (MIRAGE)	Total factor productivity baseline calibrated to take climate change into account. Yield projections obtained from crop model	Land conversion between managed and unmanaged land. Forest, pasture and crops as land cover.	(Malins 2011) - IFPRI
Partial Equilibrium (PE)			
GLObal BIOsphere Management Model (GLOBIOM)	Yields at grid level provided by crop model	Land conversion away from forest land and between cropland, grassland, managed forest, short rotation tree plantation, as well as within cropland	(Havlík et al. 2011) - IIASA
International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)	Trend terms in area and yield equations calibrated to account for climate change	Exogenous	(Rosegrant and IMPACT Development Team 2012) - IFPRI
Model of Agricultural	Vegetation growth and yields obtained from	Land conversion between cropland, pasture and	(Lotze-Campen et al. 2008) PIK

Production and its Impact on the Environment (MAGPIE)	crop model, endogenous investments into yield-increasing technological change account for adaptation	non-agricultural land	
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